REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response ... gathering and maintaining the data needed, and completing and reviewing the collection of information ... collection of information, including suggestions for reducing this burden, to Washington Headquarters ... Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget ...

AFOSR-TR-95

0640

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
1 Dec. 1993

4. TITLE AND SUBTITLE
Proceedings of the Workshop on Inherent Nonstea
Compressors and Turbines

230/OS 2549/00 and
3066/00

6. AUTHOR(S)
S.N.B. Murthy (Editor)

DTIC
SELECTE
OCT 17 1995
S D
B

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Purdue Research Foundation
Hovde Hall
Purdue University
West Lafayette, IN 47907

8. PERFORMING ORGANIZATION REPORT NUMBER
Original contains color plates: All DTIC reproductions will be in black and white

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
110 Duncan Avenue Suite B115
Bolling AFB, DC 20332-0001
Daniel B. Fant, Maj, USAF and
Dr. J. McMichael

NA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-94-1
0088

11. SUPPLEMENTARY NOTES

19951013 022

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

In the development of turbomachinery, particularly the high speed compressors and turbines, research should include in the forthcoming years the potentially promising area of inherent unsteadiness. This field is often considered to be beneficial only in the long term, and risky in its outcome. However, in view of the recognized unsteady flow features of turbomachines, it is considered timely to start a dedicated effort in pursuing a detailed understanding of unsteady phenomena from both the component and specific phenomenological perspectives. Ultimately, the focused effort should be directed to the development of a design approach that fully accounts for various features of unsteadiness, and hence, can be expected to bring about major advancement in the performance and life of turbomachinery. In mid-1993, the Air Force Office of Scientific Research approved the organization of a Workshop on Inherent Nonsteadiness in Compressors and Turbines, the so-called WINCAT. The Workshop was cosponsored by the Air Force Aero Propulsion and Power Directorate at the Wright-Patterson Air force Base, and the NASA Lewis Research Center at Cleveland, OH. The Workshop was conducted at Purdue University during October 4-6, 1993. A total of about 75 specifically invited persons from industry, government, and academia participated in the Workshop. The Proceedings of the WINCAT are presented in several parts: (a) Executive Summary of outcome; (b) Presentations; (c) Summary from discussion groups, including material from recordings during the presentations sessions; and (d) Listing of participants.

14. SUBJECT TERMS
Unsteadiness; turbomachinery; compressors; turbines

15. NUMBER OF PAGES
479

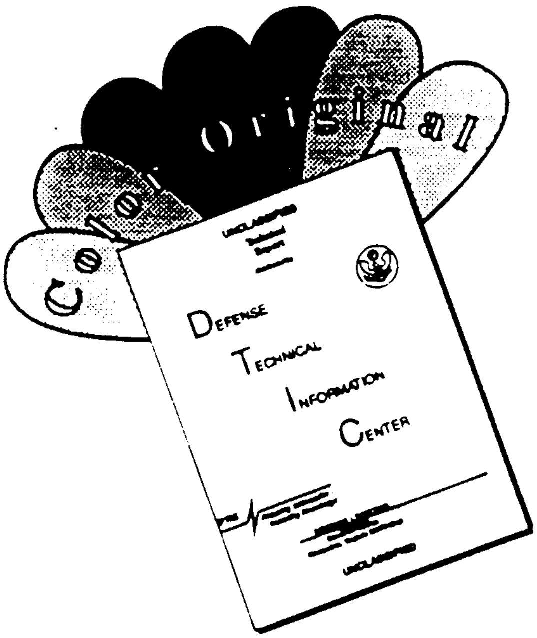
16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL (unlimited)

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF COLOR PAGES WHICH DO NOT REPRODUCE LEGIBLY ON BLACK AND WHITE MICROFICHE.

PREFACE

In mid-1993, the Air Force Office of Scientific Research approved the organization of a Workshop on Inherent Nonsteadiness in Compressors and Turbines, the so-called WINCAT. The Workshop was cosponsored by the Air Force Aero Propulsion and Power Directorate at the Wright-Patterson Air Force Base, and the NASA Lewis Research Center at Cleveland, OH. The Workshop was conducted at Purdue University during October 4-6, 1993. A total of about 75 specifically invited persons from industry, government, and academia participated in the Workshop.

The Workshop was divided into two parts: (i) invited and contributed presentations, and (ii) discussion sessions on chosen topics. Part (i) was in the nature of plenary sessions, while in part (ii) the participants divided themselves into major interest groups with occasional free movement between the groups.

The Proceedings of the WINCAT are presented in several parts: (a) Executive Summary of outcome; (b) Presentations; (c) Summary from discussion groups, including material from recordings during the presentations sessions; and (d) Listing of participants.

Information concerning availability of copies of the Proceedings may be obtained from the undersigned (Fax: 317/494-0530).

January 1994 S.N.B. Murthy

EXECUTIVE SUMMARY

In the development of turbomachinery, particularly the high speed compressors and turbines, research should include in the forthcoming years the potentially promising area of inherent unsteadiness. This field is often considered to be beneficial only in the long term, and risky in its outcome. However, in view of the recognized unsteady flow features of turbomachines, it is considered timely to start a dedicated effort in pursuing a detailed understanding of unsteady phenomena from both the component and specific phenomenological perspectives. Ultimately, the focused effort should be directed to the development of a design approach that fully accounts for various features of unsteadiness, and hence, can be expected to bring about a major advancement in the performance and life of turbomachinery.

In light of the above, and in order to set the stage for a new Air Force Basic Research Initiative in this area, the Workshop was organized with the objective of a discussion of the most crucial, unresolved flow physics issues pertaining to inherently unsteady flow features of turbomachinery, including stage interactions, compressor interactions with inlet flows, turbine interactions with combustor flows, and setting in of critical conditions. The target was an understanding of the complex phenomena, that provided the basis for improved design and effective active control strategies.

The discussions (over nearly 30 hours during 3 days) provided the needed opportunities for intensive exploration of ideas for basic research. The subject matter was considered rather sensitive in view of international competitive efforts. However, the discussions were largely open and frank. Another matter for consideration was the unavoidable emphasis on short-term goals related to product improvement required to meet market needs. However, again, it was realized that the US industry in this area maintained a reasonable balance between fundamental and developmental studies. The key was to concentrate on well focused issues and the fastest translation of basic understanding and data into product design for improvement of performance and life.

The subject matter was considered in several parts: (a) aerodynamics and flow physics, (b) heat transfer, (c) control strategies, and (d) aero-elastic performance. Analysis, modelling and predictions, and experiments were discussed individually, but with a clear focus on the necessity and benefits of a hybrid approach among them. New capabilities in computation and measurements presented the most severe challenges.

The chief causes of unsteadiness in turbomachinery are the blade passing frequency and blade row interactions in axial-flow machines and the presence of vanes and vane diffuser interactions in centrifugal machines, and the local flow instability in shear layers and vortices, driven in part by the presence of strong compressibility effects, including nonstationary shockwaves. Other causes are aero-mechanical interactions, and propagating stall and surge that are symptomatic of system instabilities. The latter arise from and also give rise to unsteadiness.

An important feature of turbomachinery unsteadiness is the presence of many different space and time scales (ranging from the system scales to small turbulence and shock oscillation scales, and to blade mechanical vibration scales) associated with the random and coherent aspects of the flowfield phenomena and structure involved. The unsteadiness, therefore, can couple easily with such other dynamical features as aerodynamic stall, freestream and shear layer turbulence, transition, distorted initial conditions, nonuniform heat transfer, and mechanical vibrations. Some of the interactive effects have been recognized and explored over the years, if only sporadically. A few of the technical areas in which advances have been sought through accounting for unsteadiness are noise reduction, generation and form of losses with a bearing on improved efficiency, structural excitation causing blade failure, extending flow stability limits

without encountering aeromechanical problems, management of tip clearance flow phenomena in high speed compressors, managing influence of inlet-generated unsteadiness on compressor dynamics, combustor-generated unsteadiness and hot streaks on turbine heat transfer, establishing transition onset and reattachement dynamics in low pressure turbines, and evolving active control strategies.

WINCAT focused on identifying and discussing approaches to unsteady turbomachinery phenomena that have the likelihood of making a strong impact on design and active control in a finite span of time. There are two issues here: one related to approaches, and the other dealing with transitioning of research findings to design. One of the main bases for developing innovative and far-reaching approaches is experimental data. In addition to powerful optical diagnostic tools for the flowfield, important advances are occurring in the use of various types of surface paints and also noncontact multi-wavelength pyrometry. In the analysis of experimental data, there is an imperative need to retain and examine time-dependent features. Unless the analysis and related computational experiments retain the full implications of unsteadiness, it is easy to miss the significance of features contained in the data sets. An important beginning has been made in predicting three-dimensional unsteady flow and also, in simulation of transition. This may provide a basis in the near future for integrated measurement-computational experiments. It may then be possible to probe such issues as separating and identifying periodic and random processes and excitations in various problems.

Some novel topics were also brought out during the WINCAT; for example, boundary layer control over blades, counter rotation of the fan-compressor unit, the effect of centrifugal action on spuriously high heat transfer in tip cooled turbines, the lag in reaching pressure equilibrium in incurred and rotational channels with respect to instantaneous excursions in velocity and possibly vorticity causing cross-transfer of large momentum, the possibility of thermo-elastic effects coupling with aero-elastic effects in the behavior of surface coatings, and the use of acoustically active surfaces. However, the main emphasis was on definitive new approaches in experimental and computational researches on the role of unsteadiness in fluids and structural mechanics of compressors and their interaction with inlet flow field dynamics, and heat transfer in turbines and its modification by the complexities in combustor exit flow.

Accounting for unsteadiness provides a direct in-road, through accounting and active control, for improving performance, stability and operability, and life cycle costs - the major drivers in industrial developments. In all these cases, there is some ambiguity in regard to the direct role of unsteadiness, and hence, the scope and need for introducing flow unsteadiness at the design level. At the same time, it has been pointed out that the cost of managing forced response problems, fundamentally related to unsteadiness, may, for example, be a surprisingly substantial part of engine cost in many cases.

Turning then to the problem of transitioning of research findings to development and design space activities, it is of prime importance to establish the influence of unsteadiness on performance, mechanical integrity, and life, with particular emphasis on the first two for improved operability. One of the chief points made by persons from industry at the WINCAT was that the greatest emphasis and care was required in choosing research topics and goals of direct relevance to turbomachinery. In general fluid flows also unsteadiness is often a feature of such processes as mixing, transition, relaminarization, separation, and heat and mass transport. Advances in such topics with a clear emphasis on unsteadiness are of great interest but generally sparse. There are few cases in which particular features and consequences of unsteadiness have been explored in the context of applications. In the case of turbomachinery the flow environment possesses a number of features that makes it almost a necessity to include such features in formulating problems even at the basic level. Both the identification of research topics as well as that of organizing and managing research were cited as issues. At the same time it was agreed that industry has been consistently cooperative in the selection and operation of research projects.

The WINCAT participants concluded that it is very important to understand and to manage unsteadiness if the design and operation is to be broadened to realize the full potential performance and operability of turbomachinery. It was strongly recommended that attention needs to be focused on the following topics: rotor-stator interactions, off-design aeromechanics, active control, film cooling, transition in low pressure turbines, turbomachinery response to initial conditions generated by an inlet and a combustor in different cases, and optimization using three-dimensional viscous-inverse techniques. Among those topics, a beginning could be made by selecting those that had near-term pay-offs so that confidence becomes established on undertaking the difficult challenges in measurement and computation.

A research initiative to address the problems was strongly recommended as both timely and valuable. It was again unanimously pointed out that engine manufacturers, government, and academia must interact thoroughly and continuously from the very inception of any program of research. Such a team effort was the only way of ensuring that the problems were addressed in the relevant context, and that the results would make a direct impact on all three of the groups.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

• PRESENTATIONS

AF OFFICE OF SCIENTIFIC RESEARCH

<u>WINCAT Workshop</u>

Turbomachinery Research

Purdue University

4 October 1993

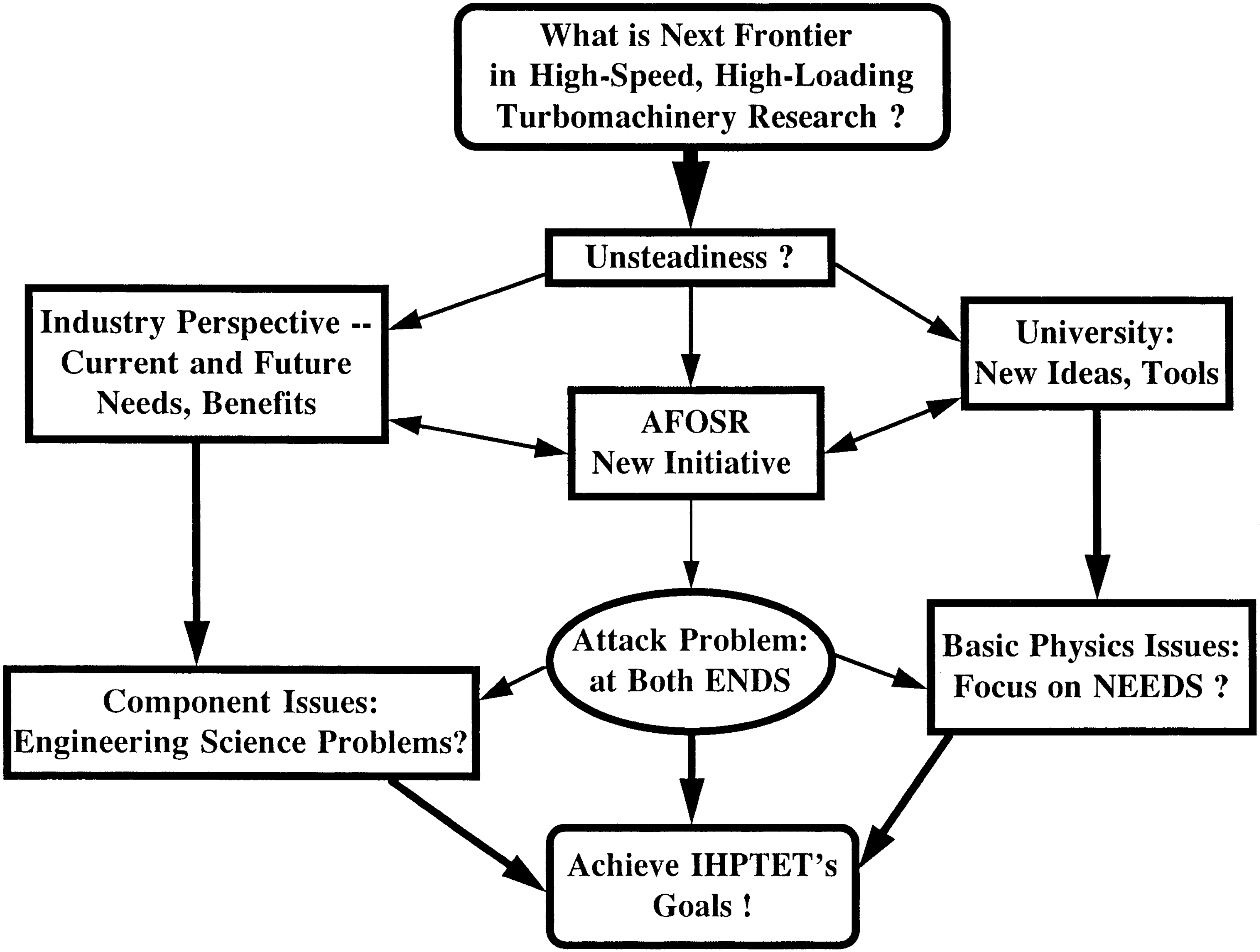
Major Daniel Fant

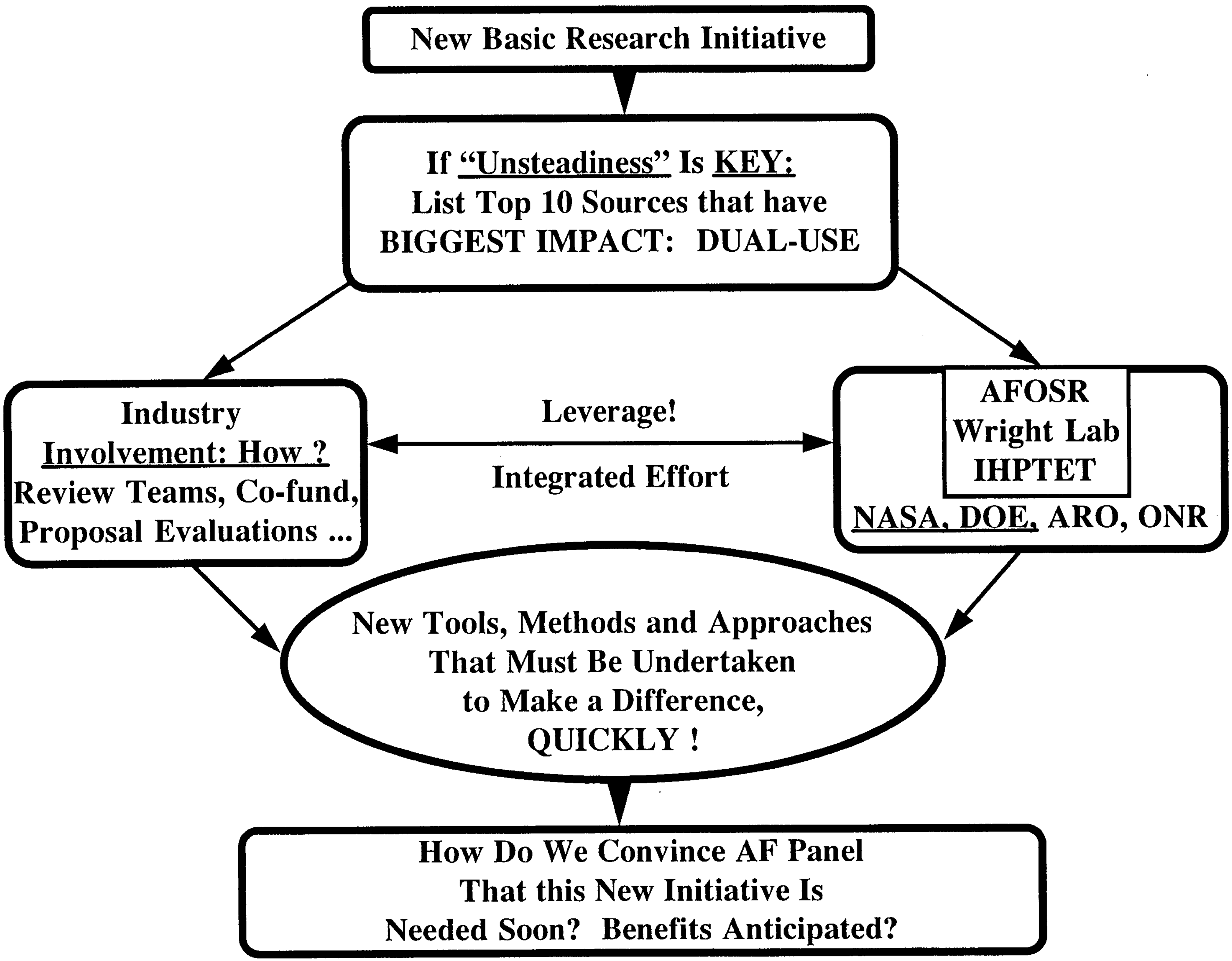
Program Manager

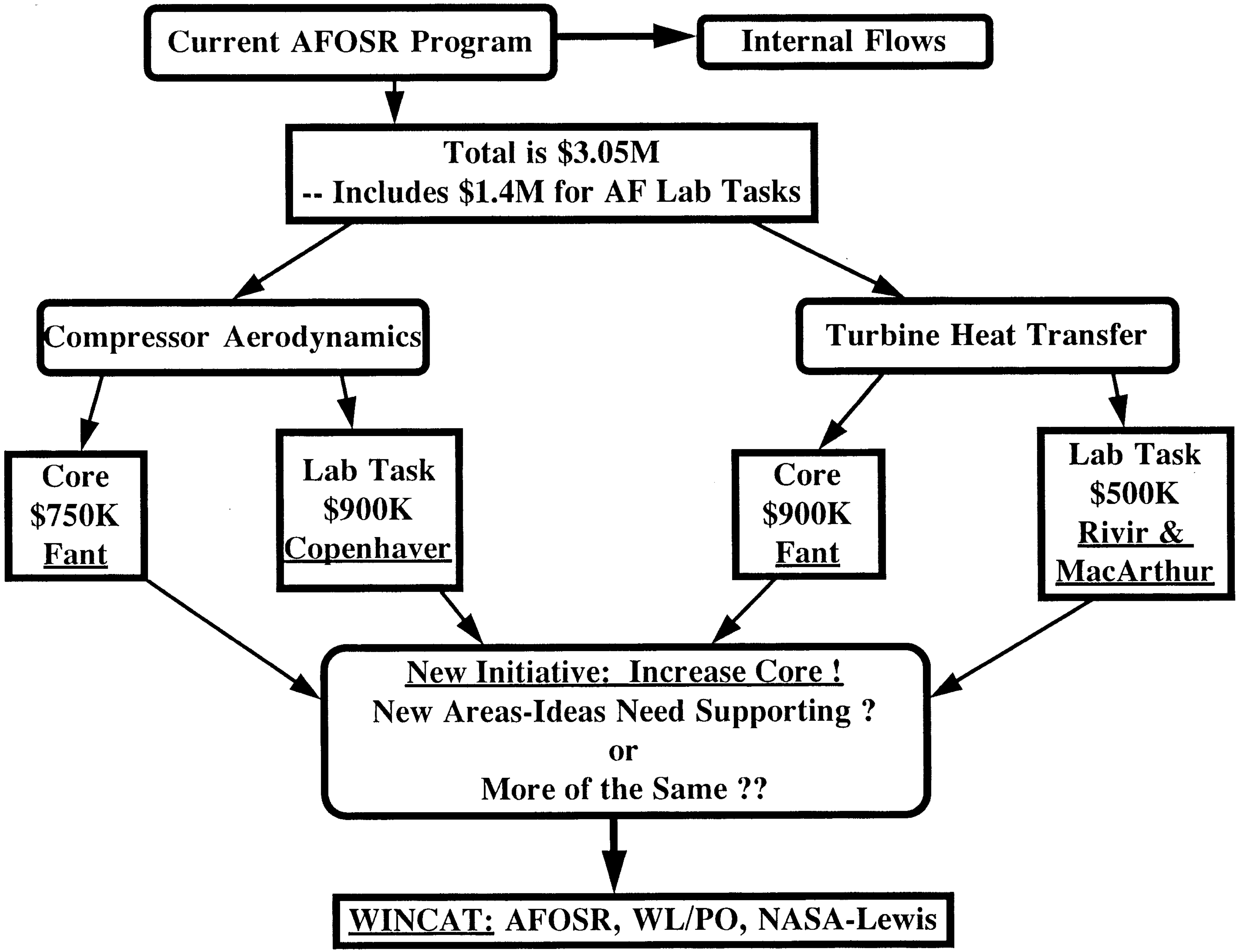
Aerospace and Engineering Sciences Directorate

202-767-0471

FAX: 202-767-4988, Email: fant@afosr.af.mil


What is Next Frontier
in High-Speed, High-Loading
Turbomachinery Research ?
Unsteadiness ?
Industry Perspective --
Current and Future
Needs, Benefits
AFOSR
New Initiative
University:
New Ideas, Tools
Attack Problem:
at Both ENDS
Component Issues:
Engineering Science Problems?
Basic Physics Issues:
Focus on NEEDS ?
Achieve IHPTET's
Goals !


New Basic Research Initiative
If "Unsteadiness" Is KEY:
List Top 10 Sources that have
BIGGEST IMPACT: DUAL-USE
Industry
Involvement: How ?
Review Teams, Co-fund,
Proposal Evaluations ...
Leverage!
Integrated Effort
AFOSR
Wright Lab
IHPTET
NASA, DOE, ARO, ONR
New Tools, Methods and Approaches
That Must Be Undertaken
to Make a Difference,
QUICKLY !
How Do We Convince AF Panel
That this New Initiative Is
Needed Soon? Benefits Anticipated?


Current AFOSR Program
Internal Flows
Total is $3.05M
-- Includes $1.4M for AF Lab Tasks
Compressor Aerodynamics
Turbine Heat Transfer
Core
$750K
Fant
Lab Task
$900K
Copenhaver
Core
$900K
Fant
Lab Task
$500K
Rivir &
MacArthur
New Initiative: Increase Core !
New Areas-Ideas Need Supporting ?
or
More of the Same ??
WINCAT: AFOSR, WL/PO, NASA-Lewis

Two Quotes In Closing

A. Comparing Great Innovators with Great Hockey Players:
"The Bent" Summer of 1993:

"Wayne Gretzky once said that he never skates to where the puck is -- he skates to where he thinks it's going to be"

-- innovation and research depend a lot on anticipating where technology will be in the future and daring to trust that intuition!

B. Parade Magazine, July 1993:

"The most important lesson of American History is the promise of the unexpected --- we must continue to be a society that is hospitable to the unexpected, which allows possibilities to develop beyond our own imaginings"

J. KERREBROCK

Massachusetts Institute of Technology

NONSTEADINESS IN TURBOMACHINERY

NONSTEADINESS IN TURBOMACHINERY

WHY DOES IT MATTER?

- NOISE
- GENERATION AND DISTRIBUTION OF LOSSES
- STRUCTURAL EXCITATION
- EFFECTS ON AXISYMMETRIC DESIGN SYSTEMS
- EFFECTS ON STABILITY LIMITS
- UNDERSTANDING

  A BASIS FOR IMPROVED DESIGNS

  INTELLECTUAL CURIOSITY

SOURCES OF UNSTEADINESS

- BLADE PASSING
- LOCAL FLOW INSTABILITY
- AEROMECHANICAL INSTABILITY - FLUTTER
- SYSTEM INSTABILITIES

  PROPAGATING STALL

  SURGE

NONSTEADINESS IN TURBOMACHINERY

WHAT DO WE KNOW?

BLADE SCALE

- EFFECTS ARE LARGE
- FLOWS ARE OFTEN NOT STEADY IN BLADE COORDINATES, eg VORTEX SHEDDING
- EFFECTS OF UPSTREAM BLADING DO NOT MIX OUT IN DOWNSTREAM BLADE ROW
- LEAD TO STRONG TRANSPORT, RADIAL AND TANGENTIAL

SYSTEM SCALE

- UNSTEADY FLOWS CAN INDICATE INCIPIENT INSTABILITY
- INSTABILITIES SUSCEPTIBLE TO INTERVENTION
- STABILITY LIMITS INFLUENCED BY UNSTEADINESS
- CONTOLLED RESPONSE AS DIAGNOSTIC FOR UNSTEADY FLOW

POSSIBILITIES FOR PAYOFF FROM RESEARCH

UNDERSTANDING

- MORE ACCURATE DESIGN SYSTEMS
- BROADENED DESIGN SPACE

TAILORING OF UNSTEADINESS

- CONTROL AND/OR REMOVAL OF VISCOUS FLOWS

  IMPROVED EFFICIENCY

  INCREASED WORK PER STAGE

- SYSTEM STABILIZATION BY ACTIVE CONTROL

  BROADENED OPERATING LIMITS

  GREATER PREDICTABILITY

  FLUTTER CONTROL

SETTING THE SCENE

WORKSHOP ON INHERENT NONSTEADINESS IN COMPRESSORS AND TURBINES

L. L. COONS

DIRECTOR

COMPRESSOR COMPONENT CENTER

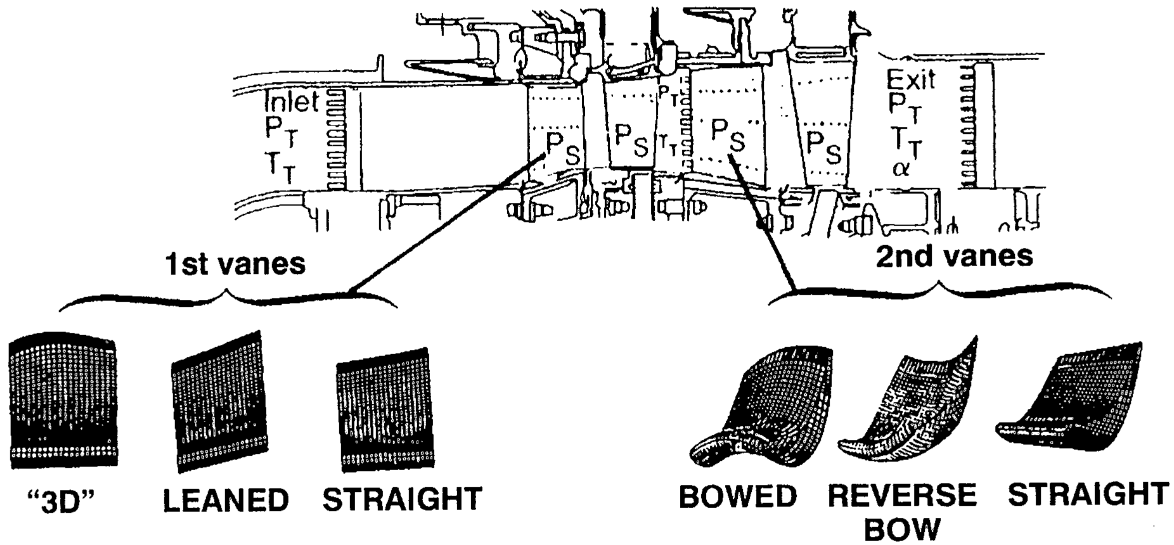
PRATT & WHITNEY

400 MAIN STREET,

EAST HARTFORD, CT 06108

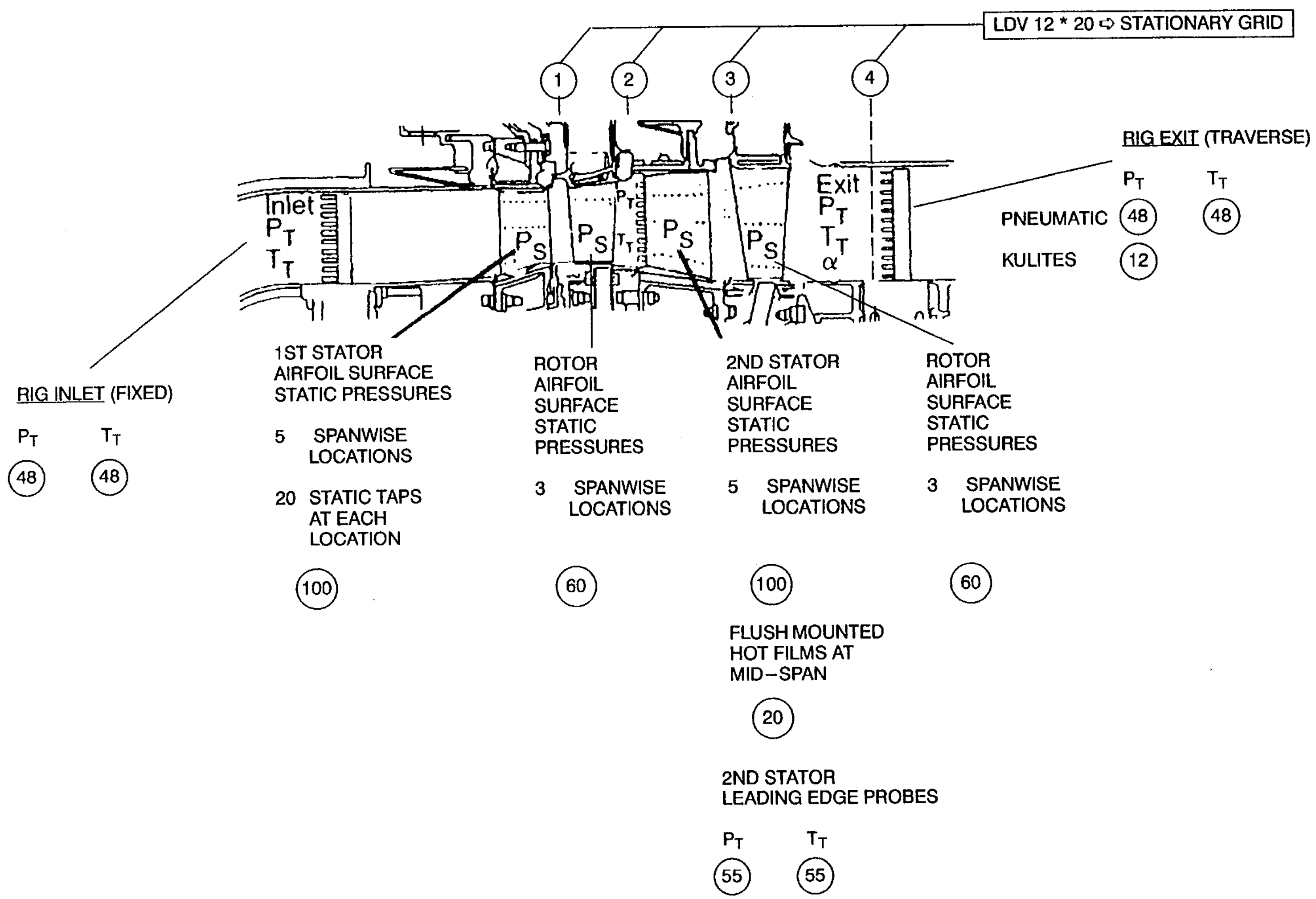
PHONE # 203–565–2382   FAX # 203–565–1345

DESIGN CONCEPTS EVALUATED IN FULL SCALE ROTATING RIGS



t930444
930929
Rev. 9/30/93

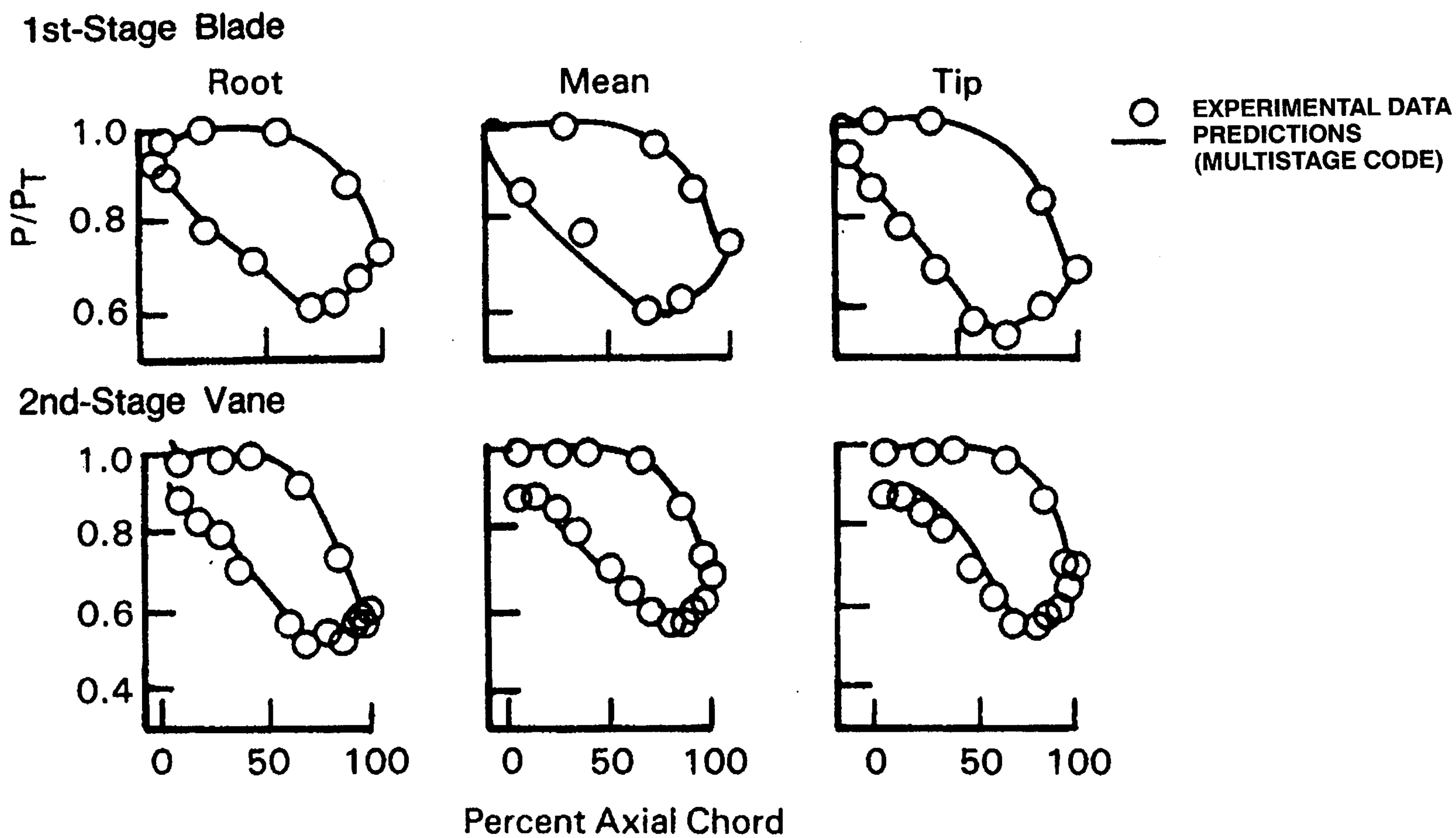
DETAILED INSTRUMENTATION UTILIZED TO MEASURE FLOW FIELD



TABULATED DATA PROVIDES LITTLE FLOW PHYSICS INSIGHT

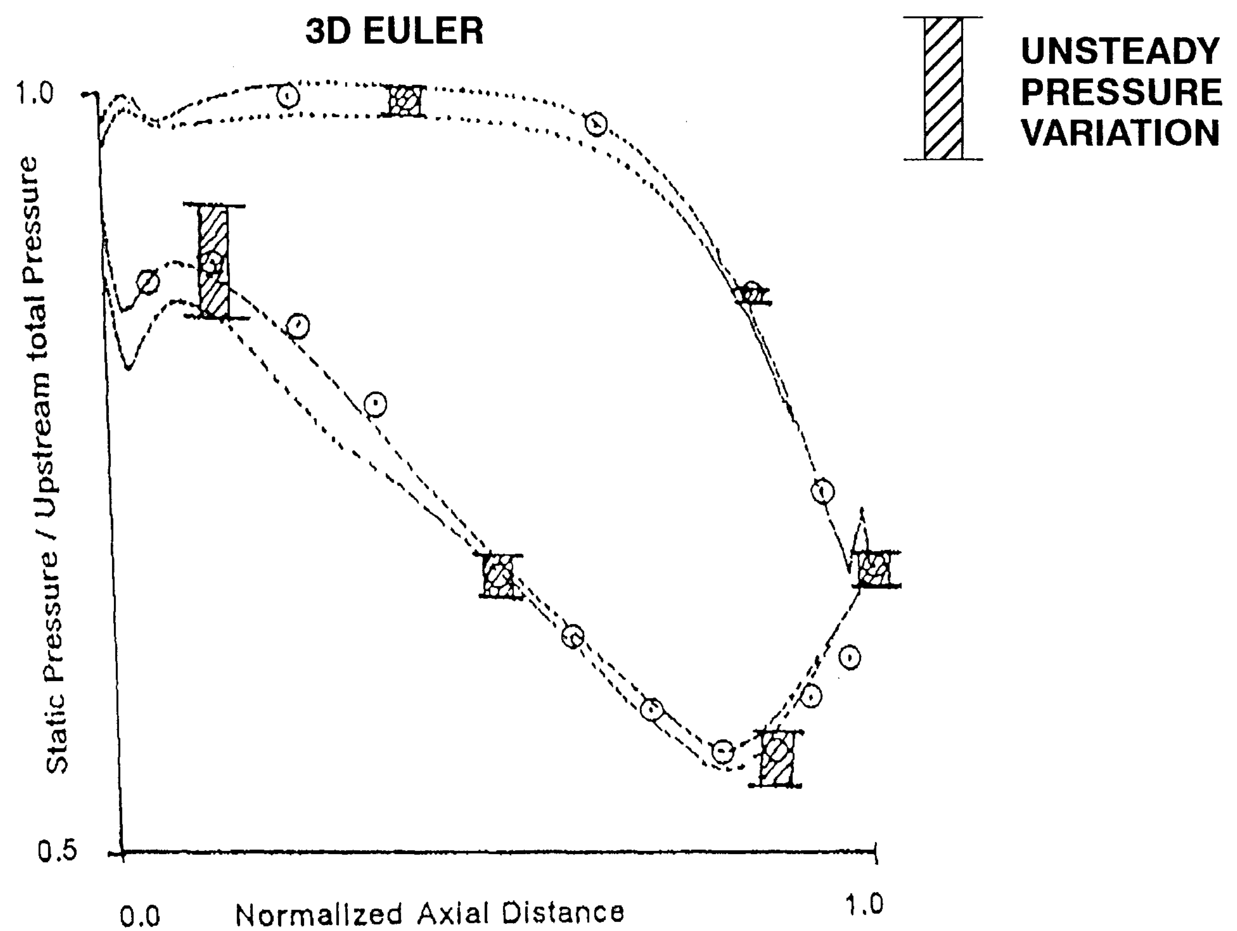
STL	RAD IN.	%SPAN	CX FT/SEC	PHI DEG	ALPHA DEG	BETA DEG	M	MREL	P PSI	PO PSI	TO DEG-R	POR PSI	TOR DEG-R	RCU FTSQ/S
1	12.58	0.00	203.74	-5.05	12.73	44.58	0.701	0.221	26.15	36.37	795.14	27.10	731.22	945.7
2	12.71	6.15	253.10	-7.42	15.84	53.17	0.704	0.241	26.28	36.62	795.06	27.40	732.04	945.2
3	12.83	11.35	273.49	-7.52	17.04	56.14	0.709	0.252	26.38	36.92	795.13	27.60	731.91	953.7
4	12.93	16.31	276.62	-6.68	17.11	56.38	0.715	0.254	26.48	37.24	795.12	27.72	730.98	968.4
5	13.04	21.28	264.92	-5.95	16.26	54.67	0.720	0.248	26.61	37.60	795.12	27.80	729.63	987.0
6	13.15	26.45	248.57	-5.34	15.17	52.55	0.723	0.239	26.76	37.92	795.13	27.87	728.40	1005.0
7	13.27	31.93	229.22	-5.19	13.99	50.79	0.721	0.225	26.92	38.09	795.12	27.92	727.80	1017.5
8	13.39	37.77	213.98	-5.25	13.13	50.43	0.716	0.211	27.08	38.13	795.12	27.97	727.99	1023.6
9	13.53	43.87	205.26	-5.28	12.71	51.67	0.708	0.199	27.25	38.11	795.12	28.05	728.68	1025.4
10	13.66	49.99	205.21	-5.05	12.84	54.61	0.700	0.191	27.42	38.09	795.12	28.17	729.65	1024.9
11	13.78	55.84	217.48	-4.49	13.71	59.20	0.695	0.192	27.58	38.13	795.12	28.34	730.64	1023.8
12	13.90	61.26	234.00	-4.06	14.87	64.19	0.691	0.197	27.73	38.17	795.11	28.52	731.78	1020.8
13	14.01	66.22	253.45	-3.72	16.24	69.19	0.686	0.206	27.86	38.19	795.11	28.72	733.08	1015.8
14	14.10	70.75	274.44	-3.36	17.77	74.29	0.680	0.216	27.96	38.14	795.09	28.91	734.76	1006.6
15	14.19	74.93	294.56	-3.06	19.26	78.78	0.675	0.227	28.06	38.09	795.13	29.11	736.51	997.0
16	14.28	78.85	305.09	-2.42	20.27	83.07	0.665	0.232	28.16	37.89	795.10	29.25	738.63	983.0
17	14.36	82.63	312.00	-1.79	21.05	86.84	0.655	0.236	28.24	37.69	795.12	29.37	740.63	970.2
18	14.44	86.40	304.38	-1.01	20.83	89.69	0.644	0.229	28.30	37.42	795.11	29.37	742.08	962.5
19	14.52	90.30	288.35	-0.02	20.03	92.39	0.633	0.217	28.34	37.12	795.12	29.29	743.30	957.1
20	14.62	94.60	247.99	1.13	17.53	95.44	0.618	0.187	28.44	36.81	795.11	29.17	744.12	955.7

INFORMATION OBTAINED FROM STEADY SURFACE STATIC PRESSURE DATA USED TO VALIDATE PREDICTION SYSTEM



4
t930444
930929
Rev. 9/30/93

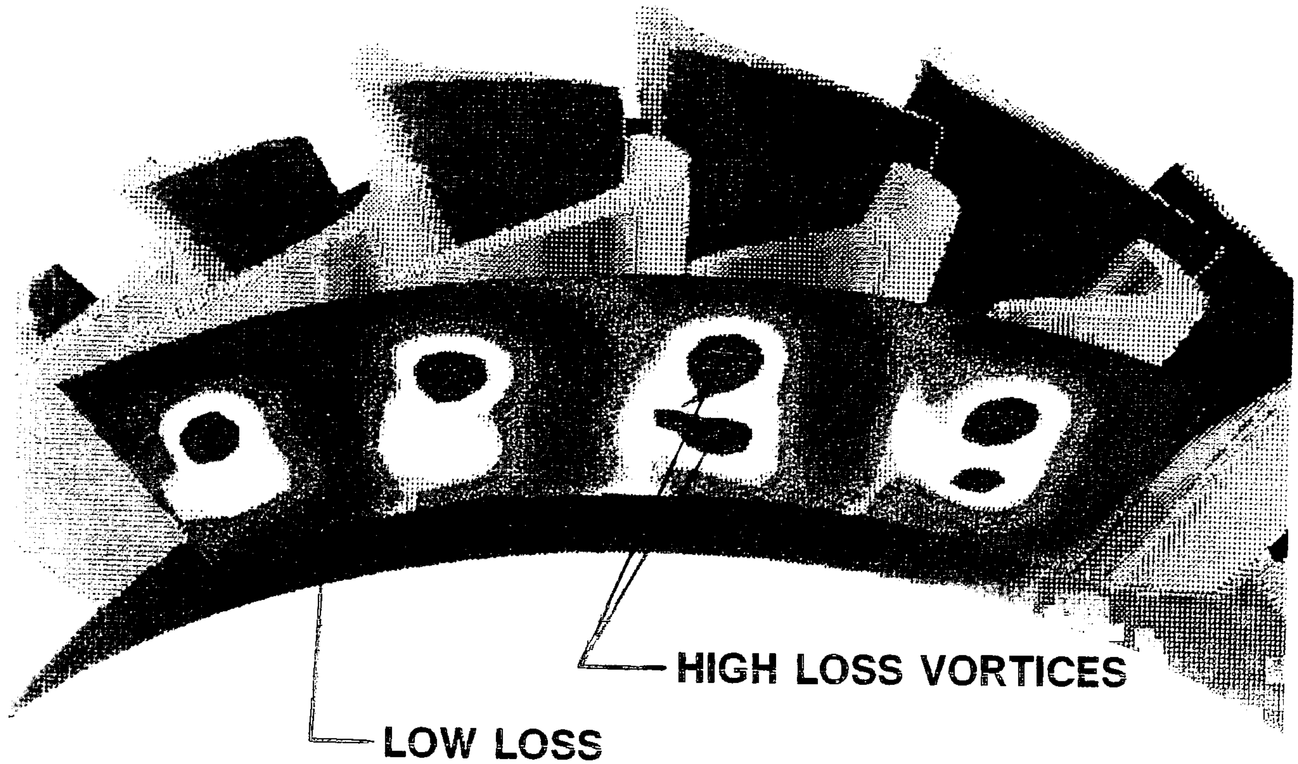
3D EULER CODE UNDER ESTIMATES UNSTEADY PRESSURES ON 2ND VANES



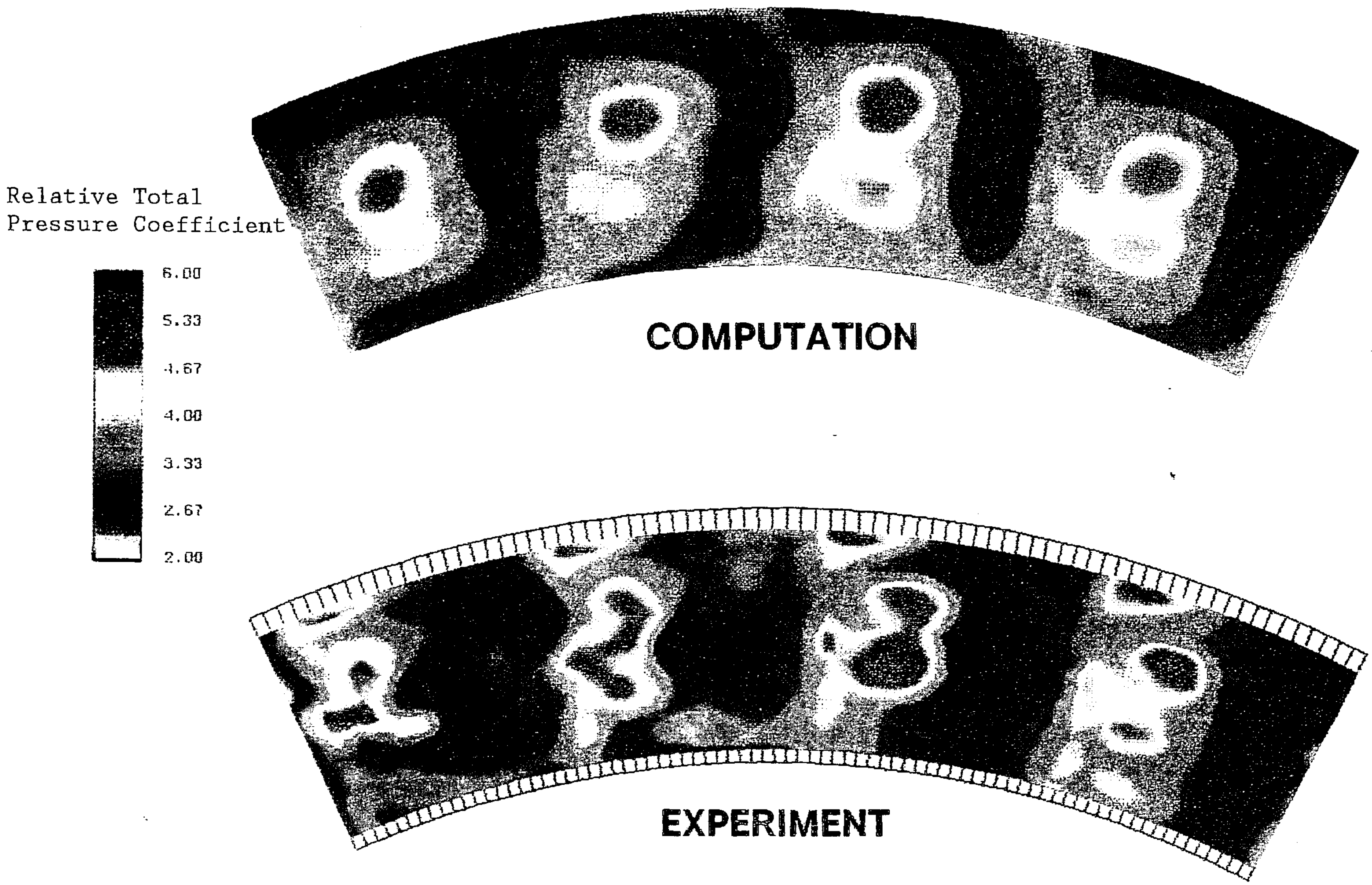
13

t930444
930929
Rev. 9/30/93

ROTOR-STATOR INTERACTION CAN BE SIMULATED BY USING CFD CODES



EULER CODE PREDICTS PROMINENT FEATURES OF UNSTEADY FLOW IN TURBINES



(b)

THE CARROT

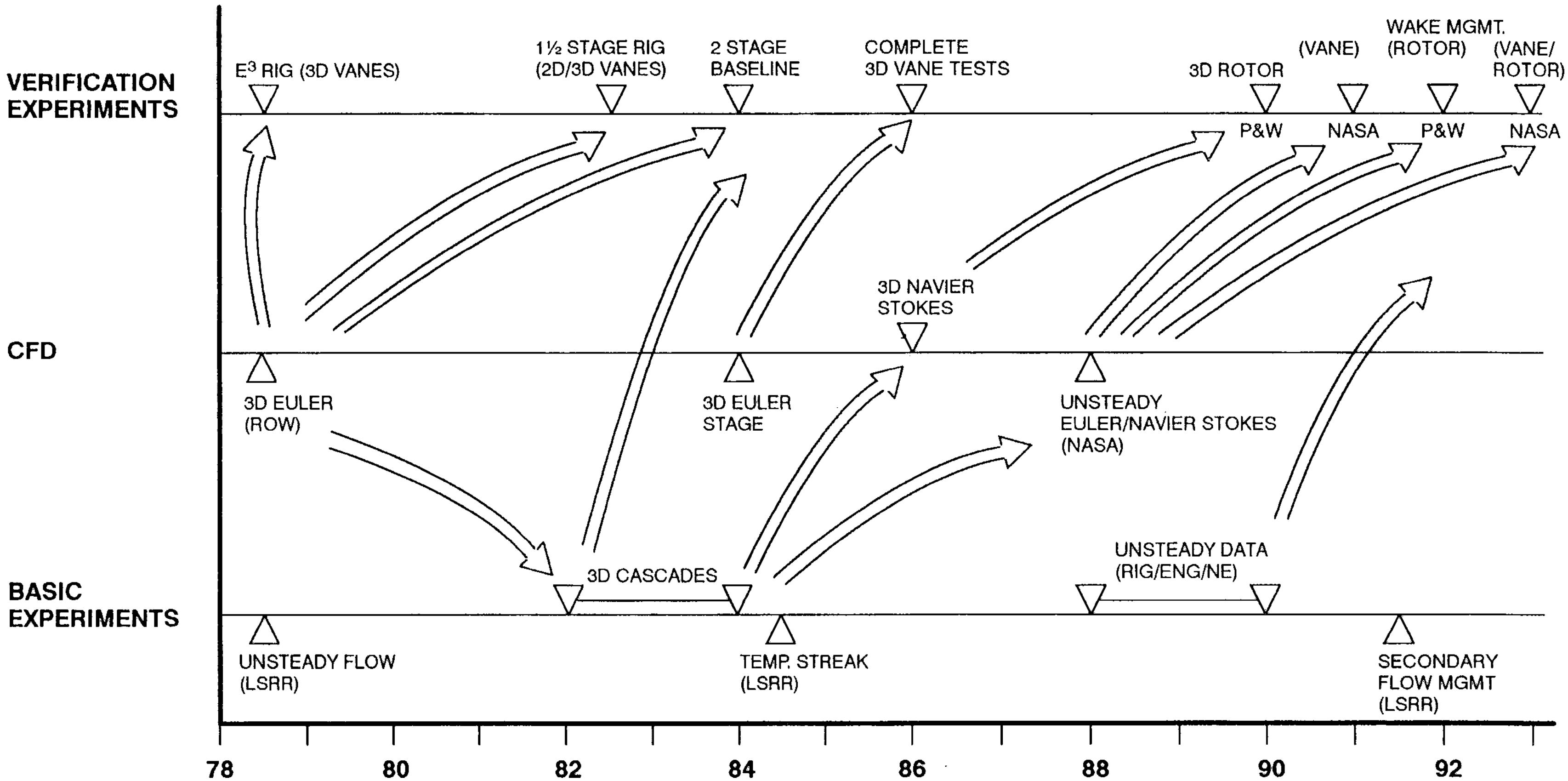
- REDUCED TIME TO MARKET
- IMPROVED PRODUCT QUALITY AND CAPABILITY

REDUCED DEVELOPMENT COST

INGREDIENTS FOR MORE INTERNATIONALLY COMPETITIVE U.S. AEROSPACE INDUSTRY

TURBINE AERO DEVELOPMENT

~ 15 YEARS AND 30 MILLION DOLLARS (AIDED BY CFD) ACHIEVED 2% IMPROVEMENT IN HPT EFFICIENCY



14

t930444
930929
Rev. 9/30/93

OUTSTANDING ISSUES

PHYSICAL MODELING

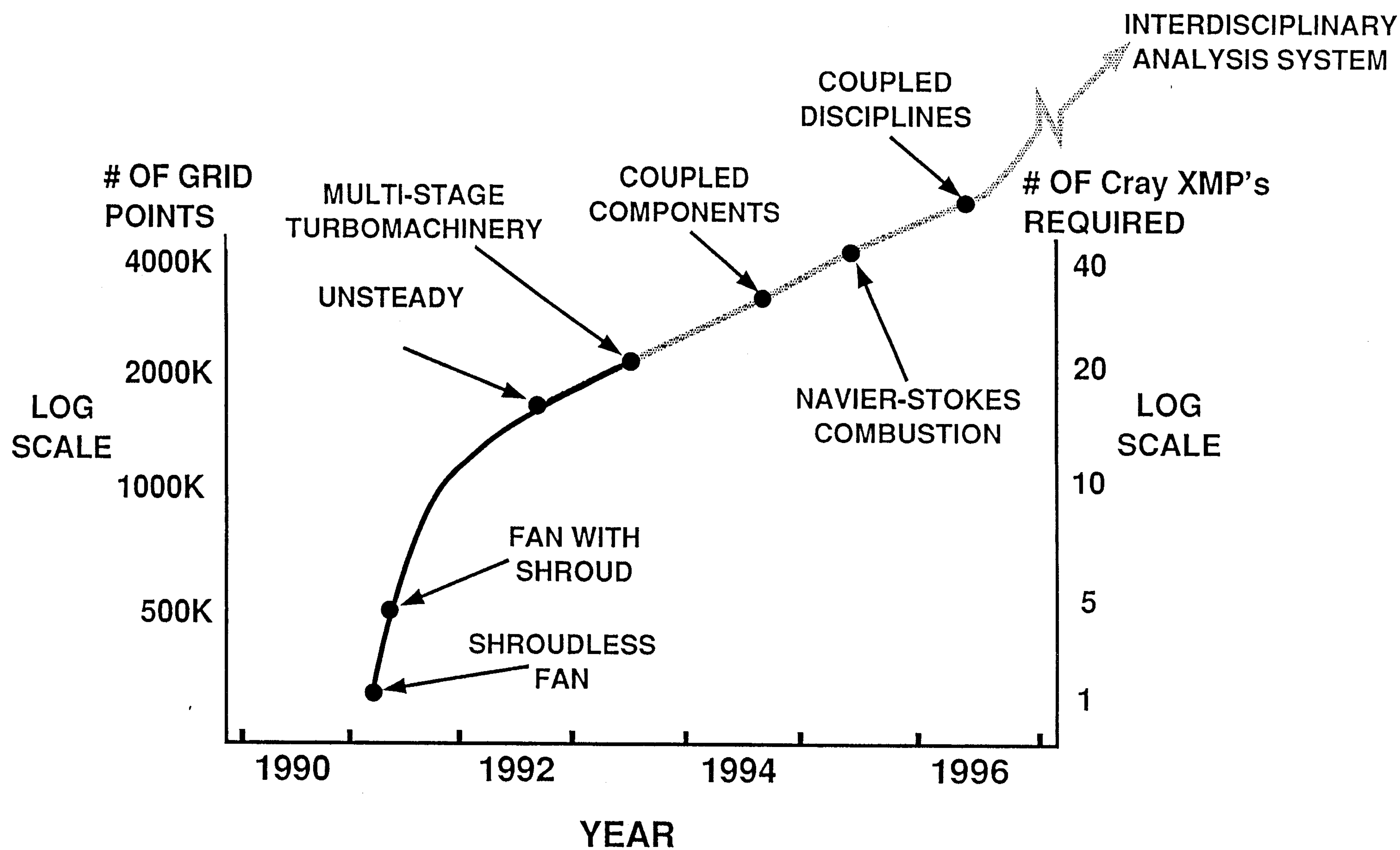
- TURBULENCE
- PERIODIC UNSTEADINESS
- SECONDARY SYSTEM FLOW INTERACTION
- FLUID STRUCTURE INTERACTION

COMPUTING CAPABILITIES

- SPEED
- STORAGE

NEXT GENERATION PRODUCT DESIGN CAPABILITY

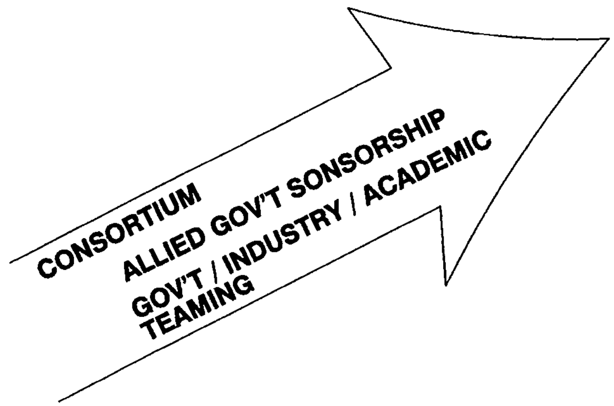
THE VISION IMPOSES SEVERE DEMANDS ON COMPUTING



dd.77

WHERE TO FROM HERE

OUTSTANDING NEEDS



VALIDATED
UNSTEADY 3D
VISCOUS PREDICTION
SYSTEM

- BETTER PHYSICAL MODELS
- INCREASED COMPUTING CAPABILITY

COMP879

UNSTEADINESS IN COMPRESSION SYSTEMS

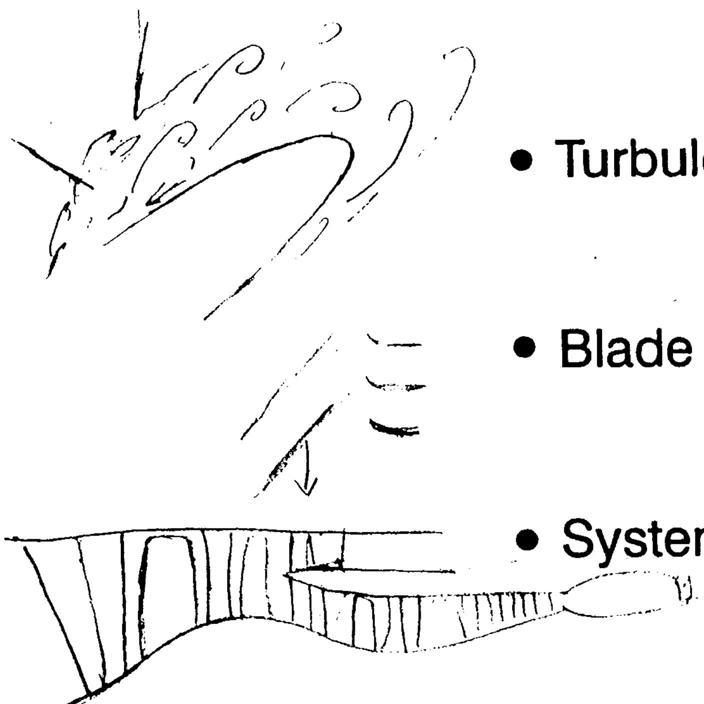
WINCAT WORKSHOP

4–6 October 1993

Dr. Sam Baghdadi
Pratt & Whitney
P.O. Box 109600
West Palm Beach, FL 33410–9600
Tel: (407) 796–2590
Fax: (407) 796–5825

WINCAT – COMPRESSOR ISSUES

Unsteadiness Inherent to Compressor Flows
Commonly and Artificially Separated into 3 Scales



- Turbulence – Scale on Order of Blade Trailing Edge Thickness
- Blade Row Interaction – Scale on Order of Blade Pitch or Chor
- System – Scale on Order of Compressor/Engine Length

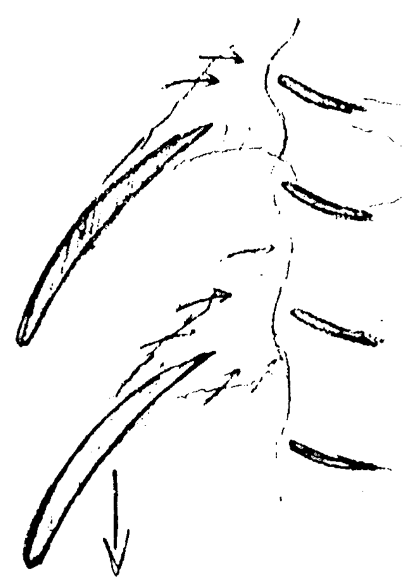
Aerodynamic, Aeroelastic, and Acoustic Performance and
Stability Driven by Unsteady Phenomena

TURBULENCE MODELLING

CURRENT PRACTICE:	Algebraic, 2 Equation Models
SHORTCOMINGS:	Anisotropy in Stresses Due to Streamline Curvature, Shock Boundary Layer Interaction
NEAR FUTURE DIRECTION:	Algebraic Stress/Reynolds Stress Models
COMMENTS:	Above Effects are Explicitly Modelled; However Length Scale Equation still Largely Empirical
LONG TERM:	Large Eddy Simulation
COMMENTS:	Natural fit with 3D Unsteady Navier Stokes which will be Needed for Multistage

BLADE ROW INTERACTIONS

Current Practice	Row Alone Analysis Interactions Accounted for Empirically
Evolving	Forces Due to Unsteady Field added into Steady Solution
Future	Fully Unsteady, Non–Periodic, Multi–Row



- Pressure Fields of Downstream Row Propagate Upstream – Unsteady Loading of Upstream Row
- Wakes of Upstream Rows Wash Over Downstream Rows – Unsteady Loading on Downstream Row

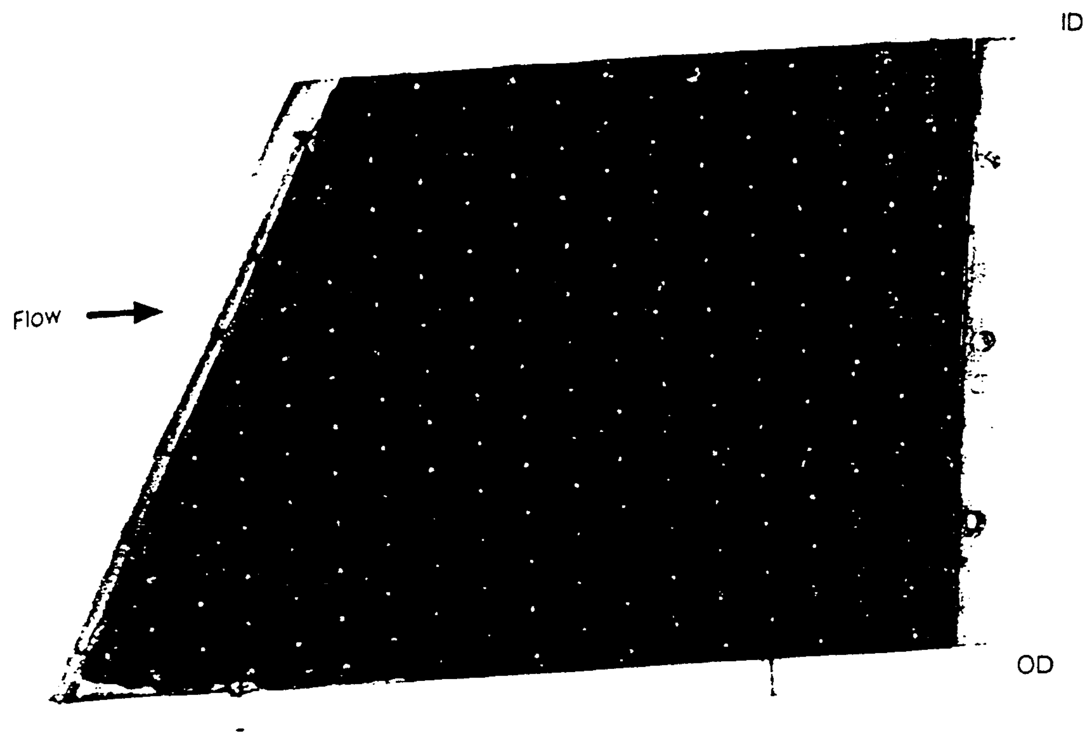


Figure 3–42.
WG_{IIa} (Spherical) Roughness Pattern

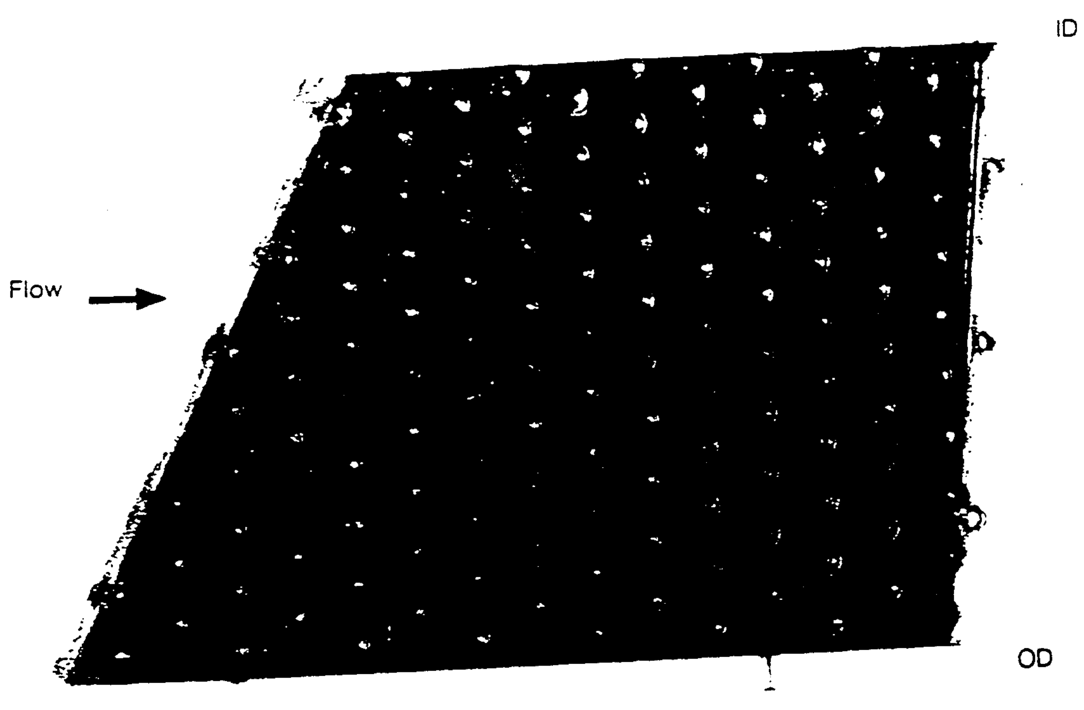


Figure 3–43.
WG_{IIb} (Conical) Roughness Pattern

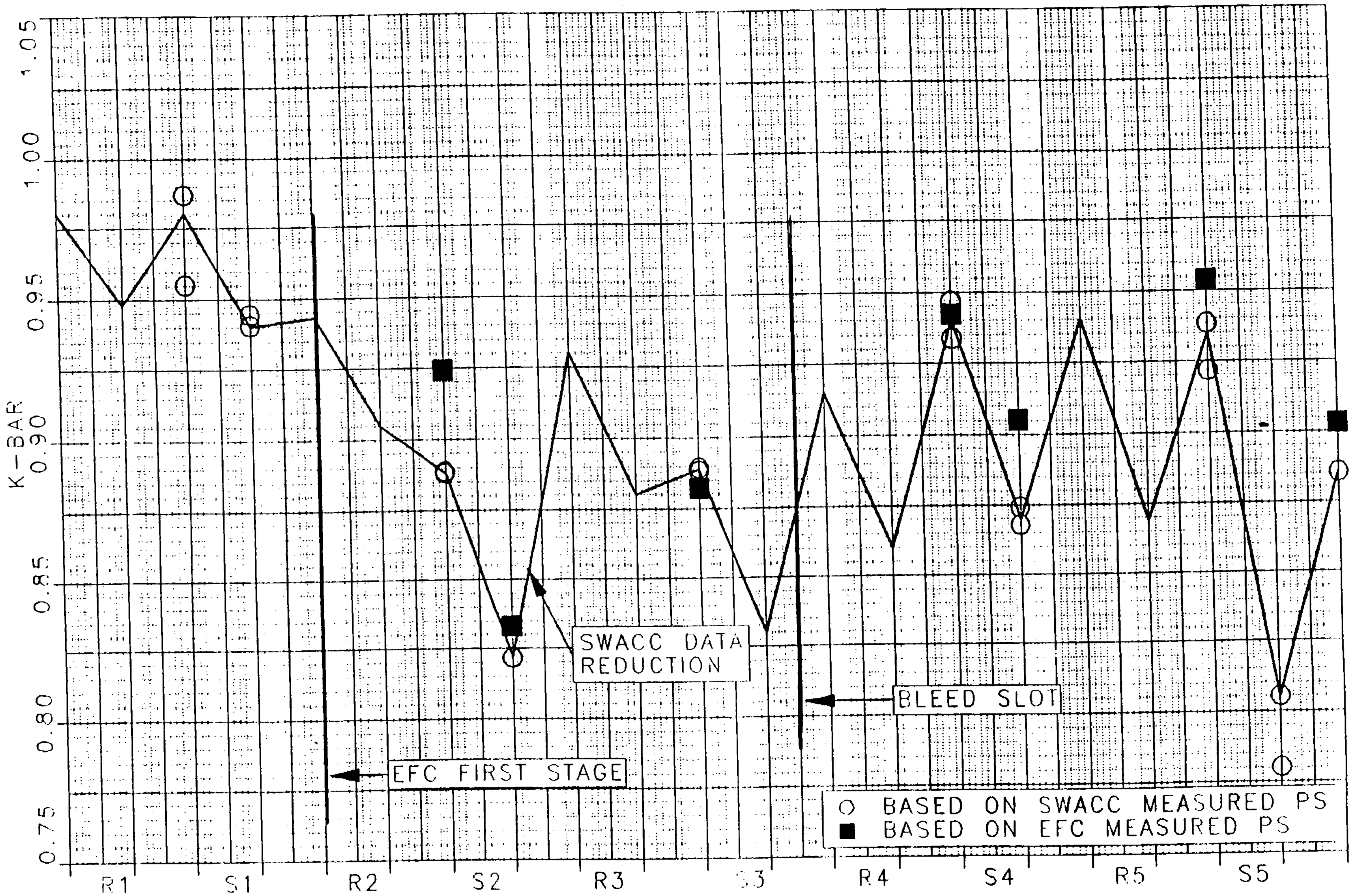
BLADE INTERACTION

Experimental Verification/Calibration of CFD Codes

- USAF/PW Stage Matching Investigation (On–Going)
  - Rotor Response to Incoming Wakes
    - Varying Intensity, Frequency, Microstructure, Mixing Distance
- Low Speed Tip Clearance Flows
  - Vary Clearance in Multi–Row Environment
  - Effects of Casing Treatments
- High Speed Compressor and Fan Data Match
  - Example: De–Staging Effects (USAF/USN/PW EFC/SWACC)
    - Repeating Stage Limit
    - Others (Usually Company Proprietary)

COMP896

DE–STAGING EFFECT ON BLOCKAGES – EFC/SWACC



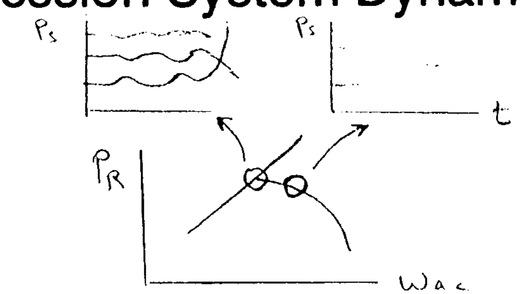
SYSTEMS

System Stability Inherently Unsteady Problem

Compression Systems Determine Overall Engine System Stability

Today

– Loading Limits are Experience–Based	– No Unsteady Physics
– Compression System Dynamic Models	– 1–D, Unsteady Row–by–Row
	– Empirical or Calculated 1–D Characteristics

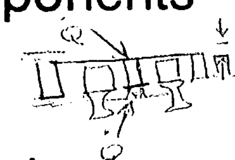


Future

– Propulsion System Simulation Models

Incorporate Detailed, High Frequency Models of all Engine Components

1–D ➤ 2–D ➤ 3–D Unsteady



Include Thermal Environment Modelling and Inlet Distortion Effects

COMPONENT APPLIED ISSUES

COMPRESSORS

WINCAT
OCT 4-6, 1993
WILLIAM W. COPENHAVER

TYPES OF UNSTEADINESS AND IMPACTS

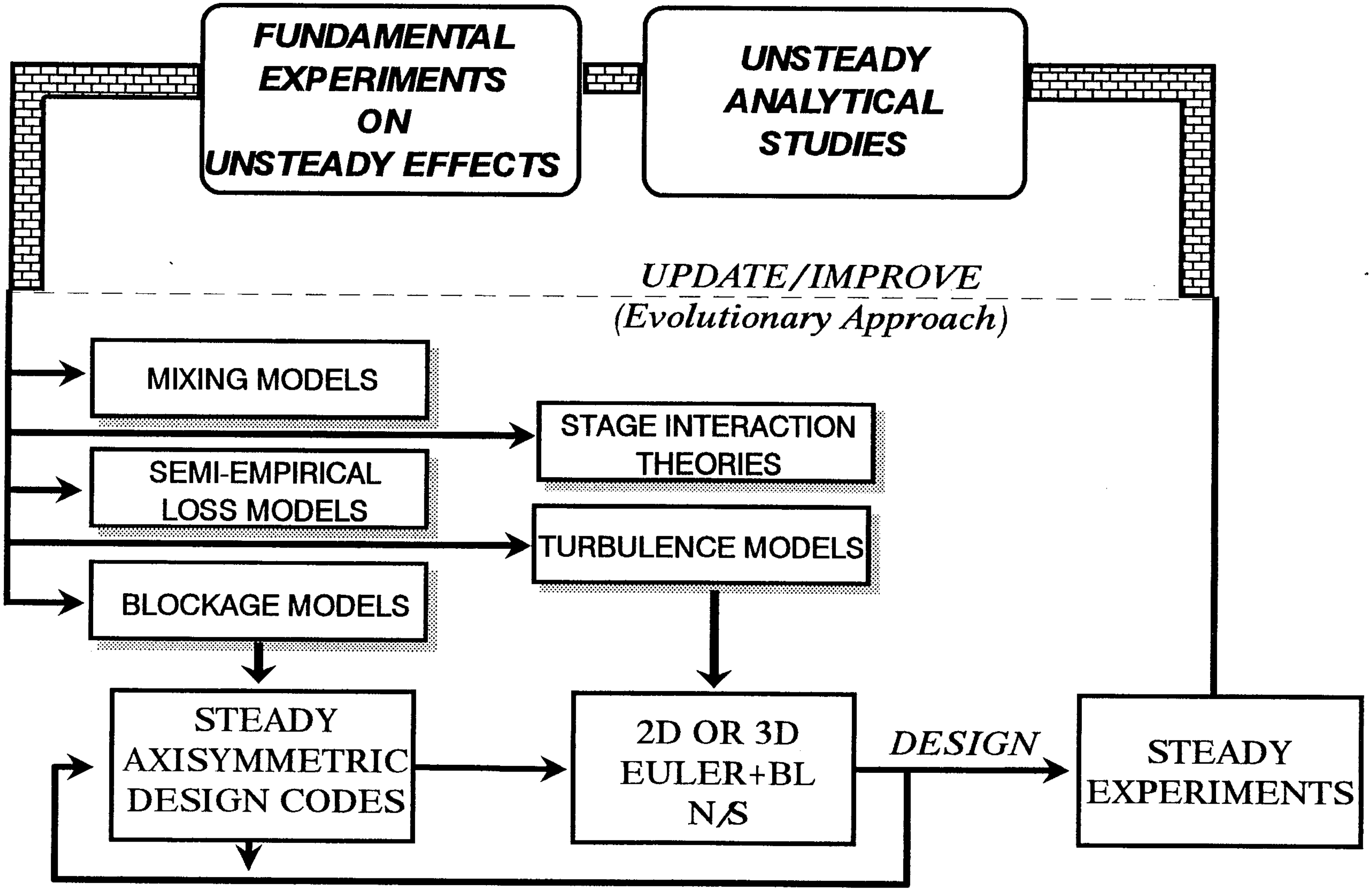
- LONG LENGTH SCALE
  - SURGE (COMPRESSOR LENGTH)
  - INLET DISTORTION (SEVERAL BLADE PASSAGES)
  - ROTATING STALL(SEVERAL BLADE PASSAGES)
- MEDIUM LENGTH SCALE (BLADE PASSAGE)
  - WAKES (ROTOR/STATOR)
  - POTENTIAL FIELDS
- SHORT LENGTH SCALE
  - TURBULENCE
  - VORTICITY SHEDDING

- IMPACTS
  - EFFICIENCY, OPERATING RANGE, LOADING LEVELS
  - MATCHING, AEROMECHANICAL ROBUSTNESS, DURABILITY

ISSUES

- HOW WILL THE DESIGNER TAKE ADVANTAGE OF UNSTEADINESS
  - DESIGN SYSTEM CURRENTLY STEADY IN NATURE
  - BLOCKAGE AND LOSS MODELS NOT TAILORED FOR FLOW PHYSICS
  - UNSTEADY CFD COSTLY, TIME CONSUMING AND STORAGE INTENSIVE
- WHICH LENGTH SCALE IS KEY TO IMPACTS
- WHAT ROLE DOES UNSTEADINESS PLAY AS STAGE LOADING INCREASES

DESIGN SYSTEM NEEDS



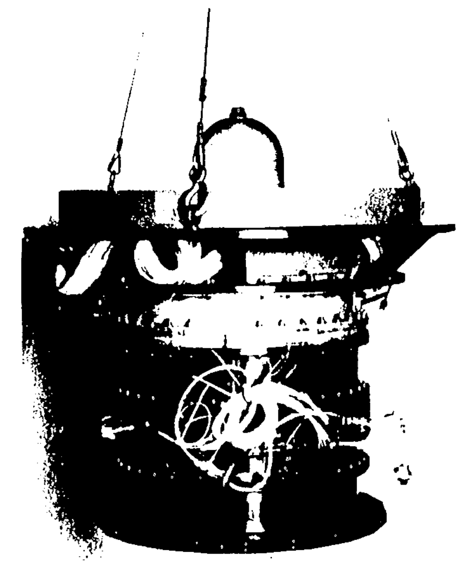
PATHWAYS FOR KNOWLEDGE

PATH	ROADBLOCKS	TRANSITION POTENTIAL
ANALYTICAL 2-D UNSTEADY	• CALIBRATION	• NEAR TERM DIRECT • NEAR TERM MODEL IMPROVEMENTS
ANALYTICAL 3-D UNSTEADY	• HIGH COST/TIME • DATA STORAGE REQ.	• FAR TERM DIRECT • NEAR TERM MODEL IMPROVEMENTS
LOW SPEED EXPERIMENTS	• LOADING LEVELS	• NEAR TERM MODEL IMPROVEMENTS
HIGH SPEED TRANSONIC FLOW EXPERIMENTS	• COST/TIME • DIAGNOSTICS	• FAR TERM MODEL IMPROVEMENTS

WL UNSTEADY FLOW RESEARCH
PROGRAM GOALS

INVESTIGATE THE EFFECTS OF WAKE:

- FREQUENCY
- MACROSTRUCTURE
  - WIDTH
  - VELOCITY DEFECT
  - PROXIMITY
- MICROSTRUCTURE
  - TURBULENCE LEVEL
  - SHEDDING FREQUENCY



ON:

- FLOW SWALLOWING CAPABILITY
- AEROMECHANICAL FORCED RESPONSE
- STAGE AERO PERFORMANCE
- STALL MARGIN

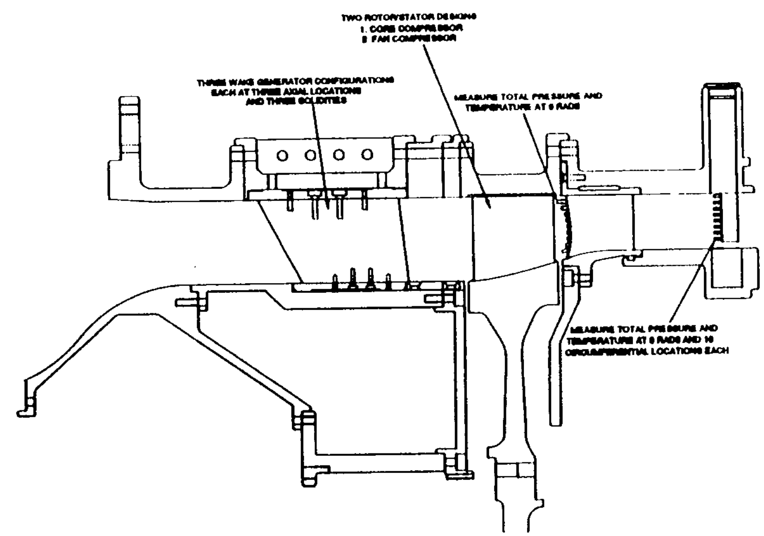
RIG DESIGN FEATURES

VARIABLE WAKE GENERATOR

- ROUGHENED VANES
  VARY WIDTH AND TURBULENCE
- 12, 24, OR 40 VANES
  REDUCED FREQ 2 TO 8
- FAN, HPC, CLOSE PROX SPACING
  VARY WAKE MIXING
- TRAILING EDGE STINGER
  SHEDDING FREQ 7760-7980-59,680 HZ

CORE AND FAN STAGE

WAKE CALIBRATION

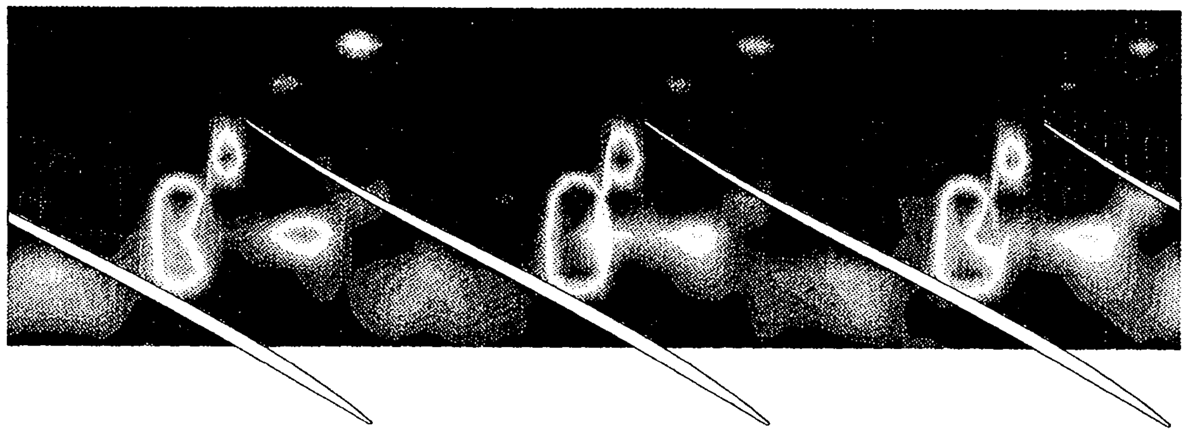


ROTOR DESIGNS

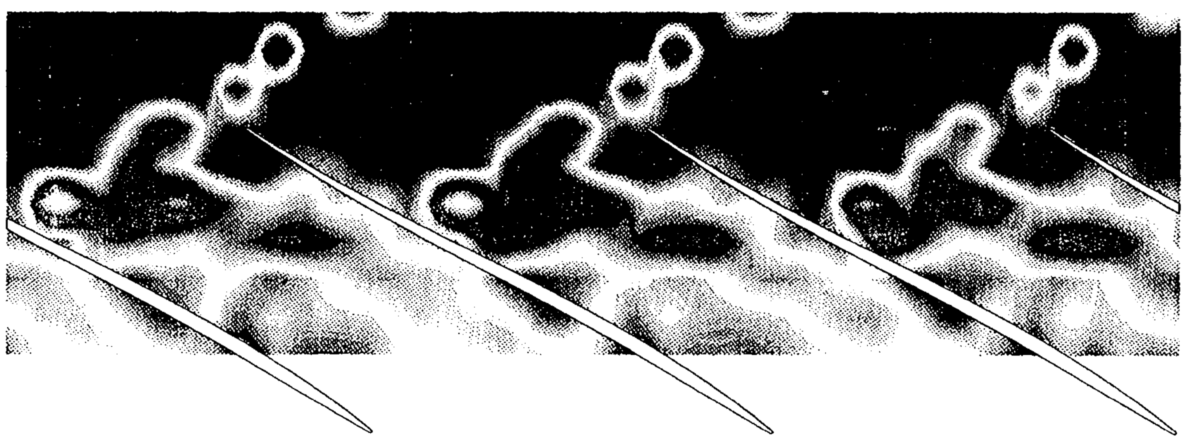
	FAN	COMPRESSOR
TIP SPEED	1360 ft/sec	1120 ft/sec
TIP RELATIVE MACH #	1.389	1.191
HUB RELATIVE MACH #	1.1	0.963
# BLADES	28	33
ASPECT RATIO	.916	.961
INLET HUB/TIP RADIUS RATIO	0.75	0.75
FLOW PER ANNULUS AREA	40.0 lb/sec/ft**2	40.0 lb/sec/ft**2
FLOW RATE	34.46 lb/sec	34.46 lb.sec
PRESSURE RATIO	2.18	1.88
EFFICIENCY	0.91	0.935

WL TRANSONIC FAN SHOCK LOSS RESEARCH

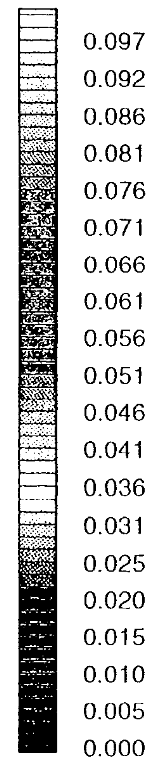
RMS STATIC PRESSURE LEVELS



ROTOR PEAK EFFICIENCY



ROTOR NEAR STALL



SUMMARY

- A FOCUSED PROGRAM IS REQUIRED FOR SUCCESS
- WL WILL PARTICIPATE WITH EXPERIMENTAL AND ANALYTICAL RESEARCH
- KEY TO TRANSITION: GEAR FINDINGS TOWARD DESIGN SYSTEM EVOLUTION NEEDS

Robert P. Dring

United Technologies Research Center

COMPONENT APPLIED ISSUES II: TURBINE

Workshop on Inherent Nonsteadiness in Compressors and Turbines

(WINCAT)

October 4 - 6, 1993

Purdue University

Component Applied Issues II: Turbine

Robert P. Dring

United Technologies Research Center

Outline

- Unsteady airfoil pressures
- Potential-flow and wake interactions
- CFD simulations and airfoil count ratio
- Boundary layer and turbulence issues
- Random and periodic unsteadiness
- Heat transfer and unsteadiness
- Rectification
- Inherent Nonsteadiness issues

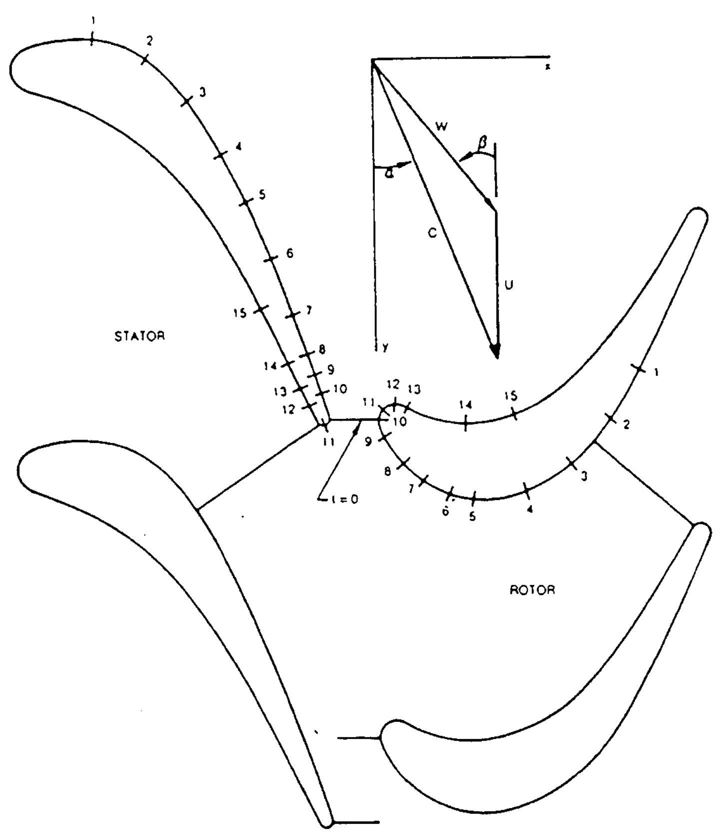
Background

- Axial gaps between adjacent airfoil rows are in the range of 10% to 60% of airfoil axial chord.

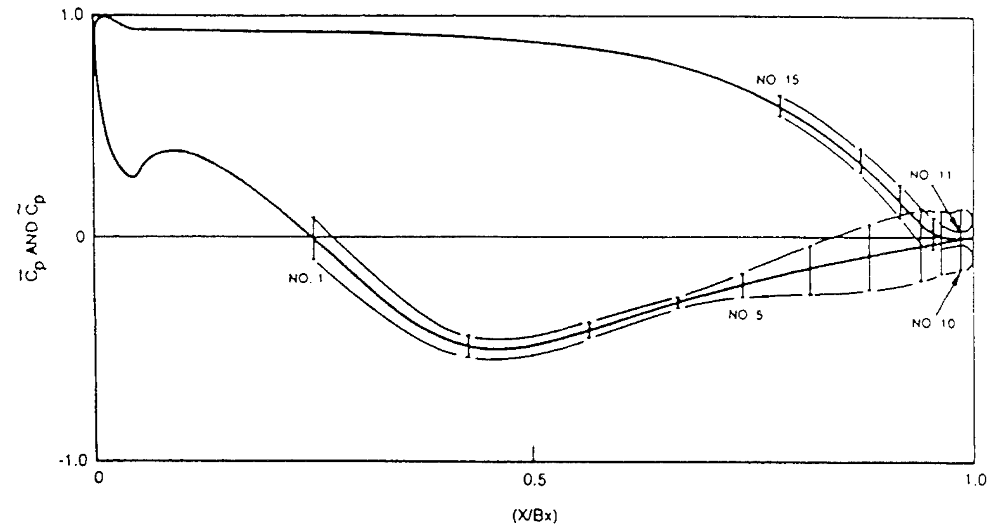
This presentation is based on material extracted from work by the following people.

- David Joslyn UTRC
- Larry Hardin UTRC
- Mike Blair UTRC
- Dick Roback UTRC
- Roger Davis UTRC
- Om Sharma P&WA
- Tom Butler P&WA
- Dan Dorney Western Michigan Univ.
- Howard Hodson Whittle Labs.
-

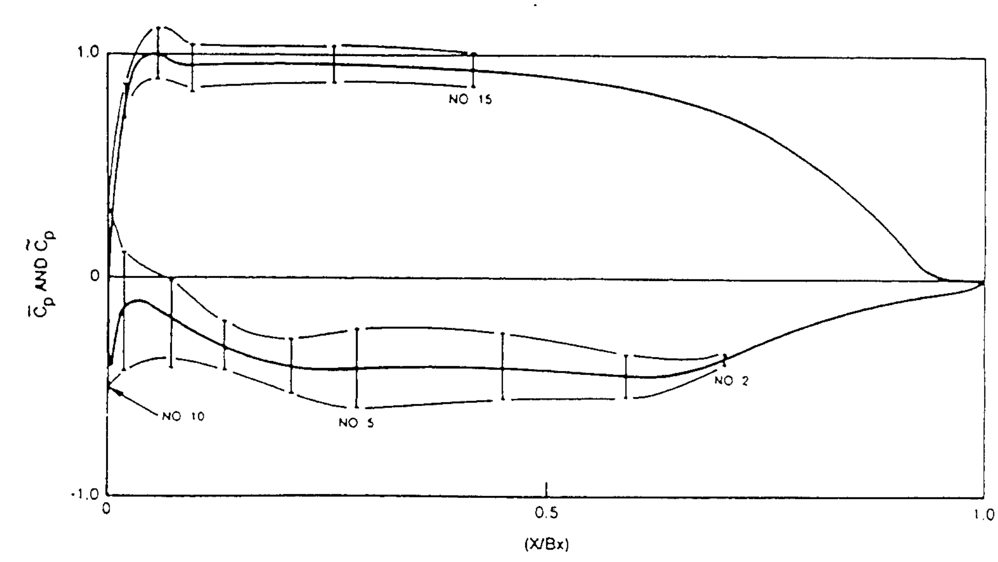
Turbine Stage at 15% Gap (Kulite Sites)

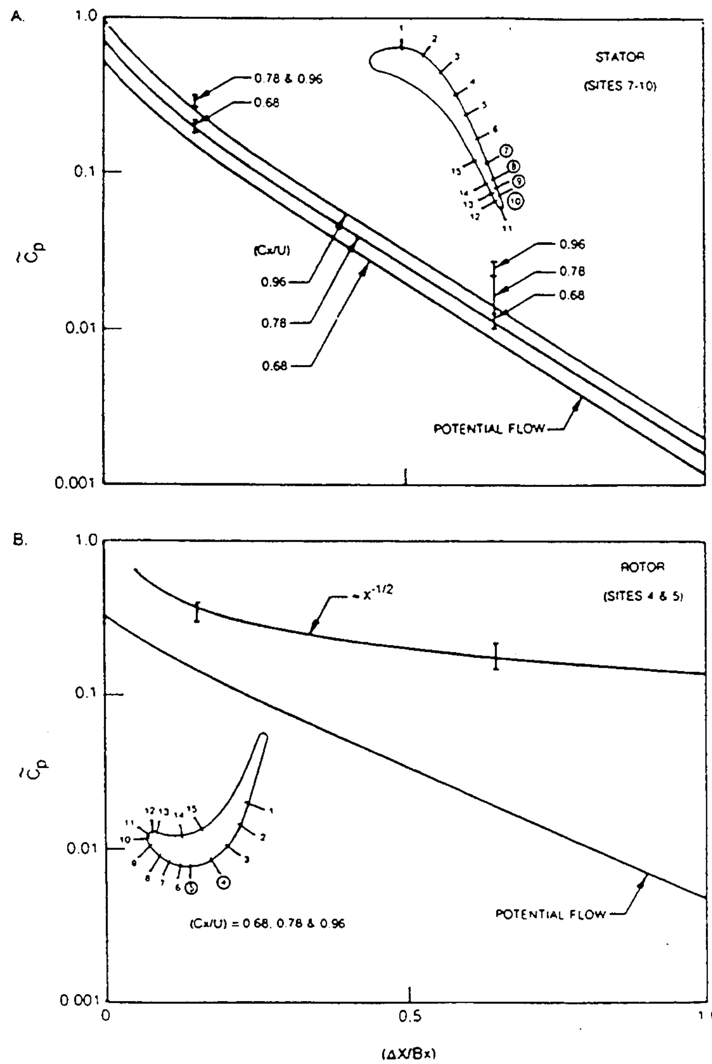


Stator Unsteady Pressure Envelope, 15% Gap, $(C_X/U) = 0.78$



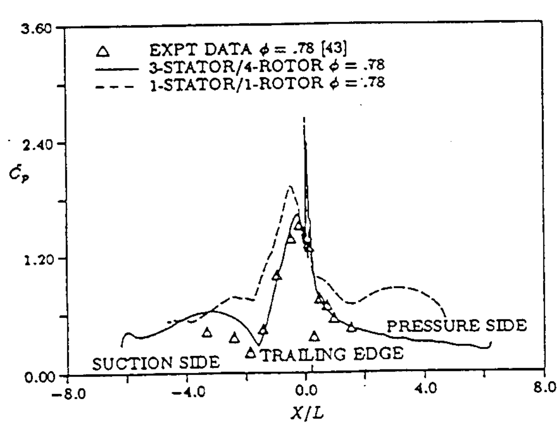
Rotor Unsteady Pressure Envelope, 15% Gap, $(C_X/U) = 0.78$



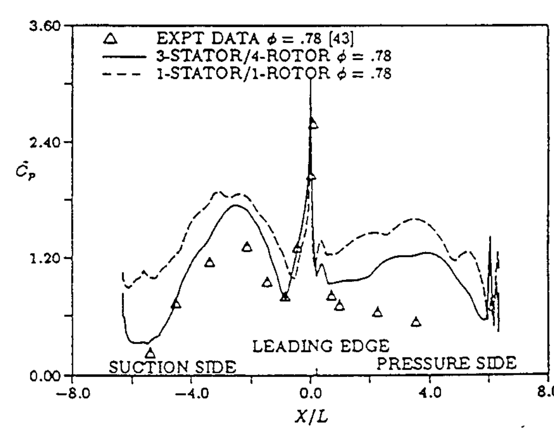


Decay of Unsteady Pressure Amplitude With Axial Gap

Time-accurate Navier-Stokes calculations have demonstrated that pressure amplitude is sensitive to stator/rotor count ratio.

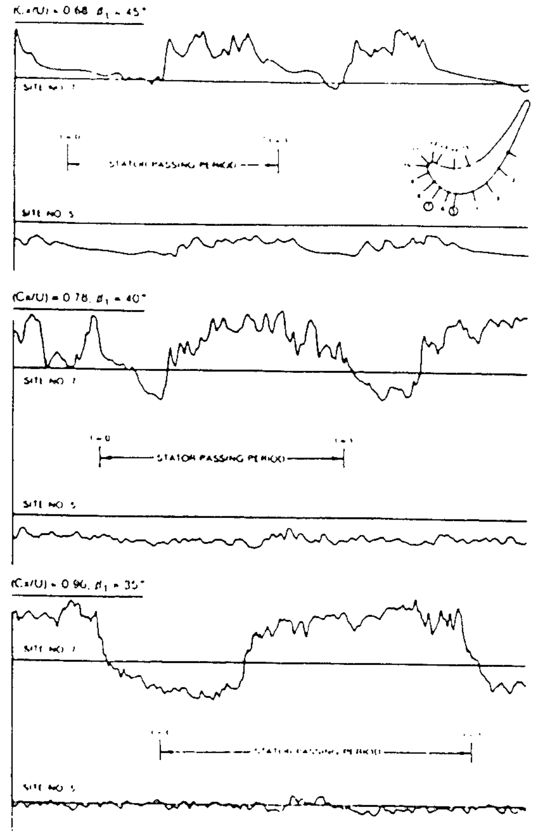


Stator

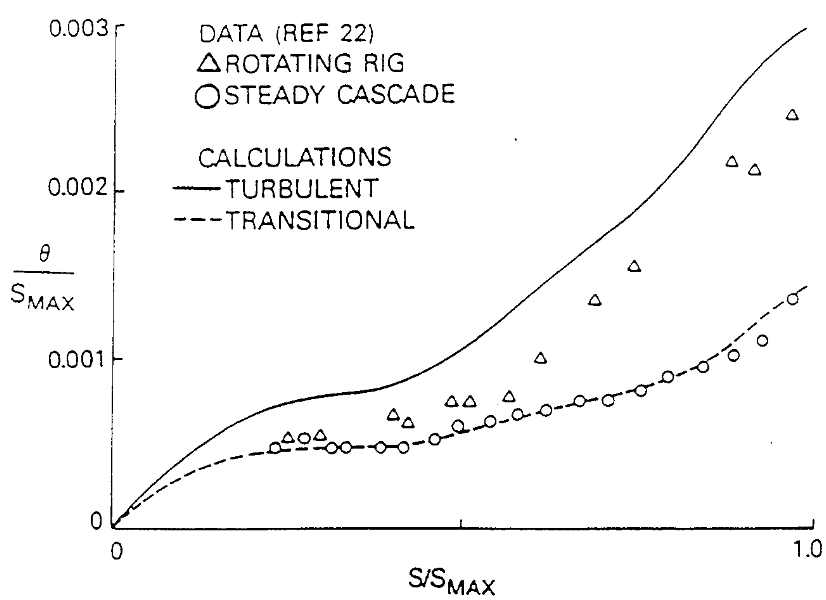


Rotor

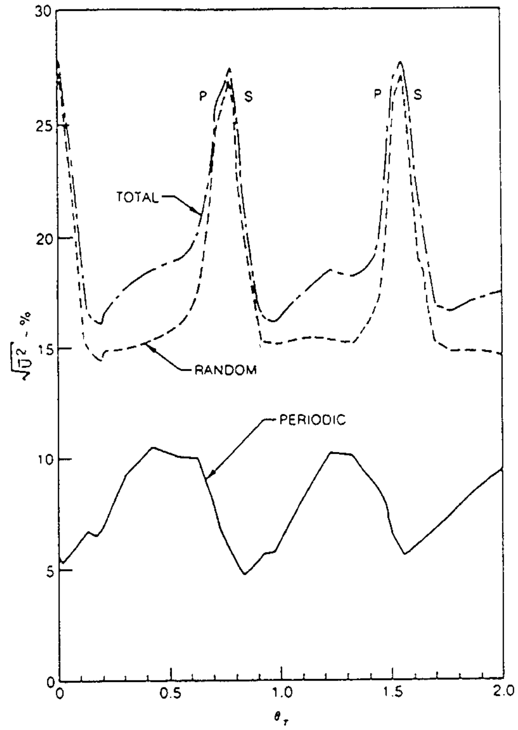
Rotor Thin Film Data, 65% Gap

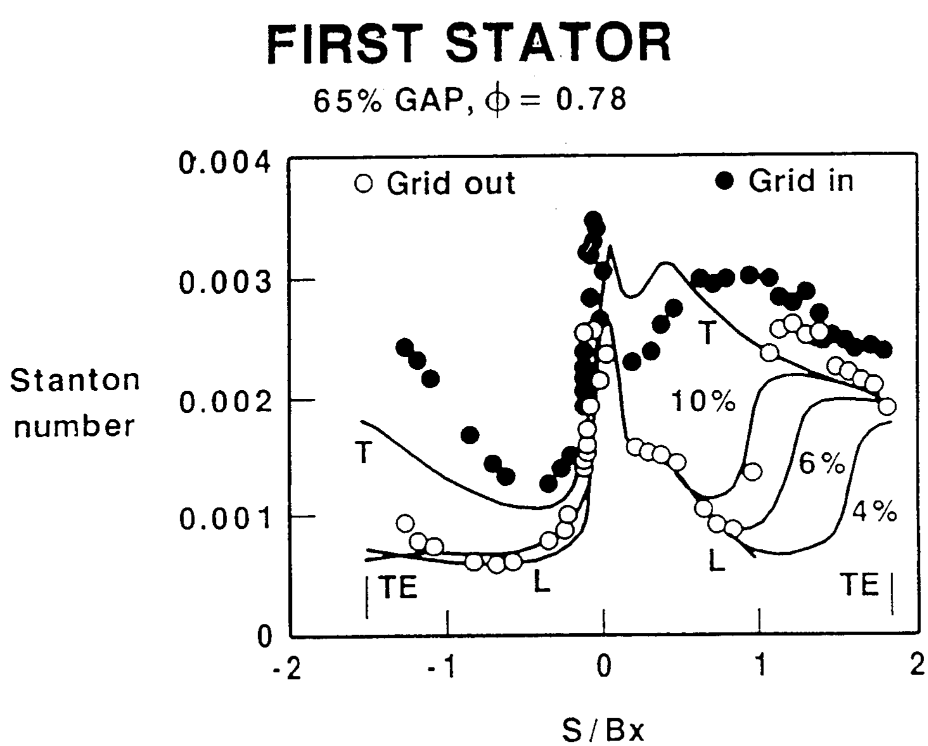


Boundary layer momentum thickness in an unsteady rotor environment (Hodson) is bracketed by steady cascade data and turbulent calculations.

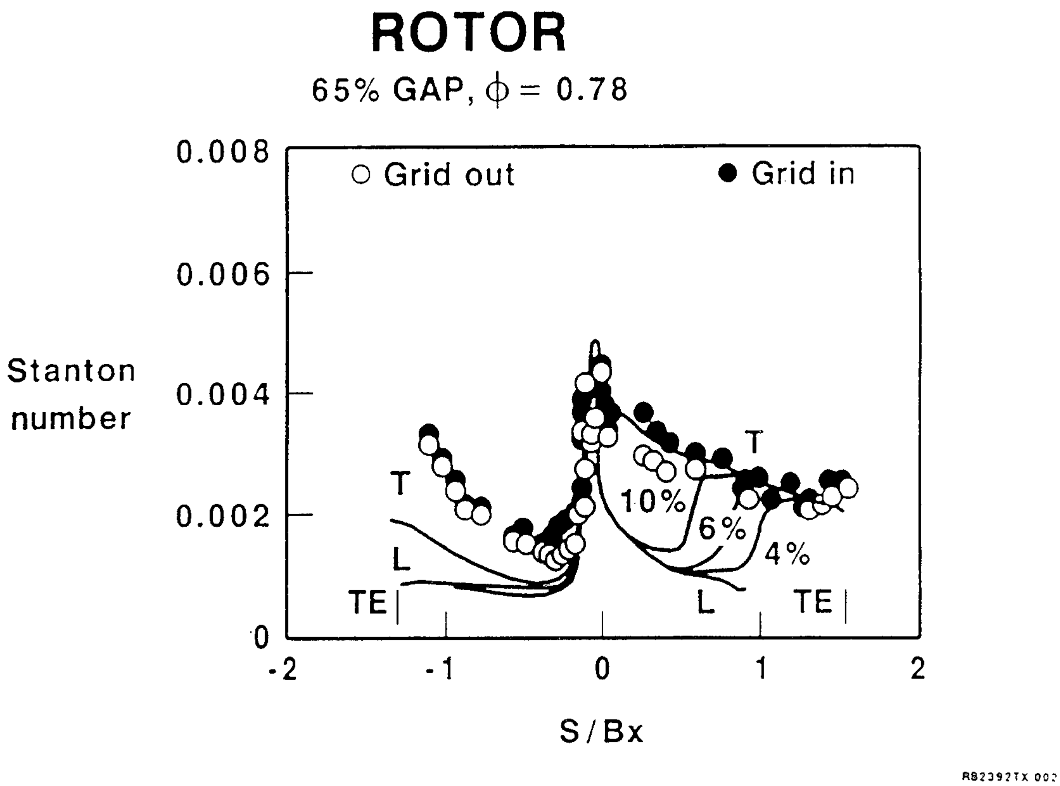


As seen in the unsteadiness in the flow at the second stator exit, total unsteadiness is composed of comparable random and periodic contributions.

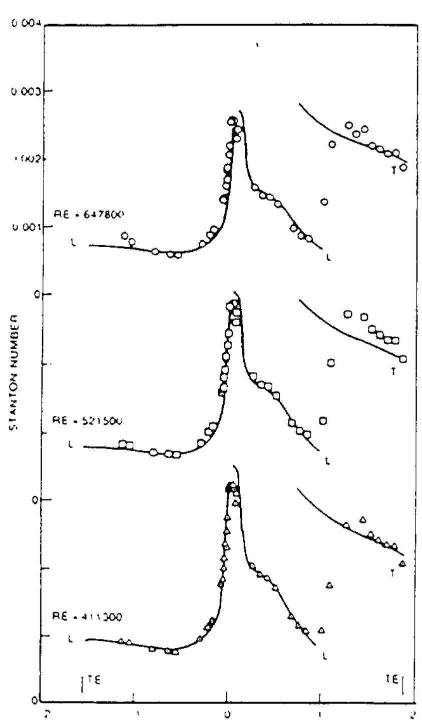




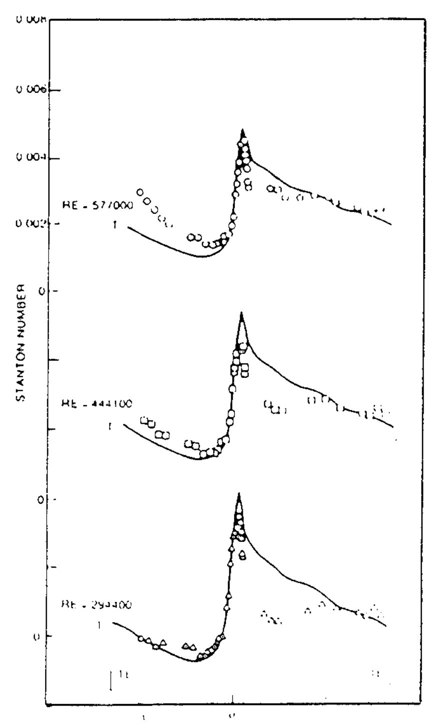
RB2392TX.001

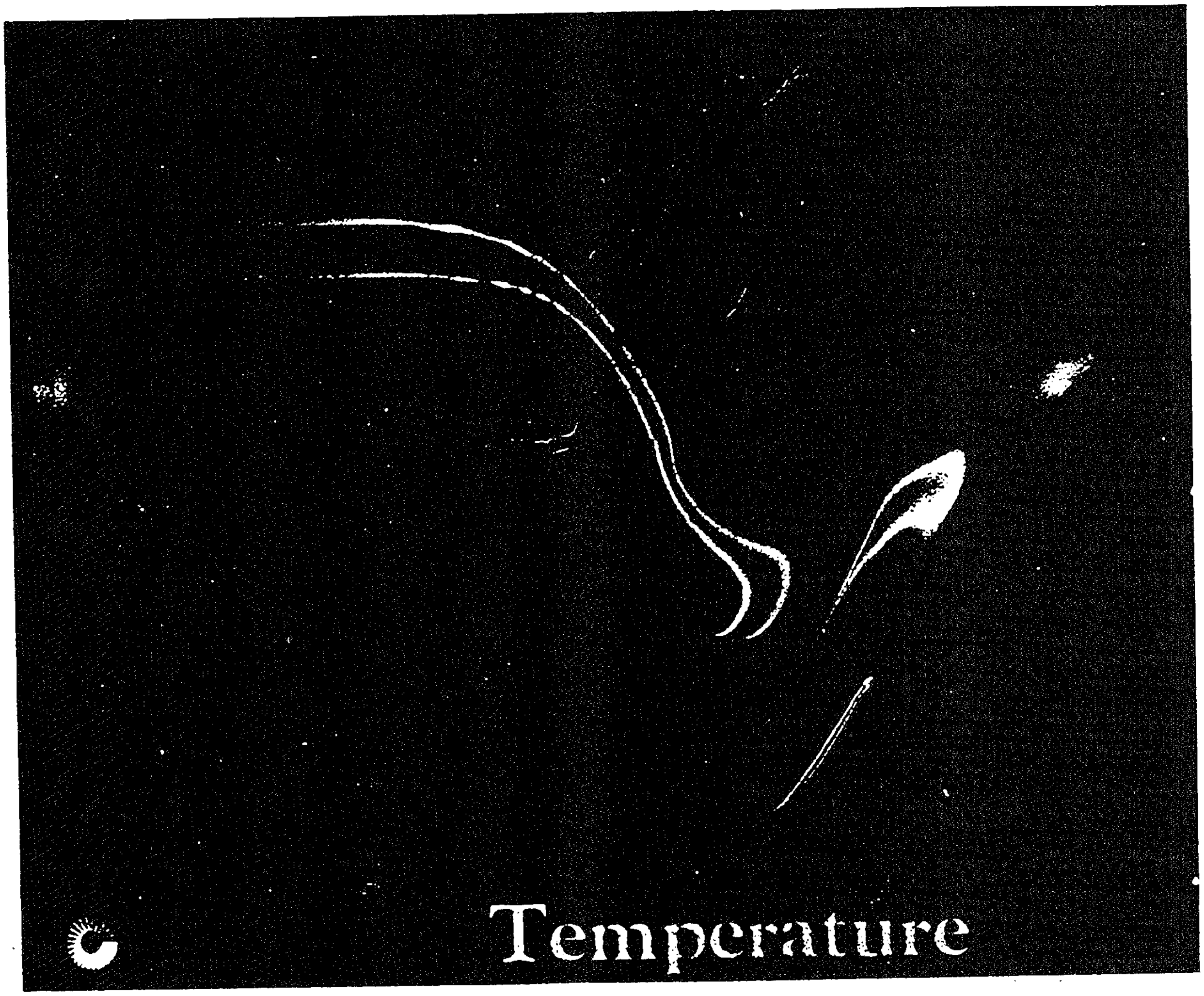


Effect of Reynolds Number on the First Stator Heat Transfer, Grid Out

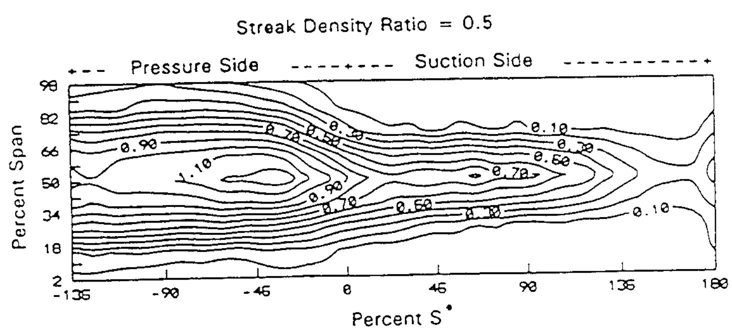


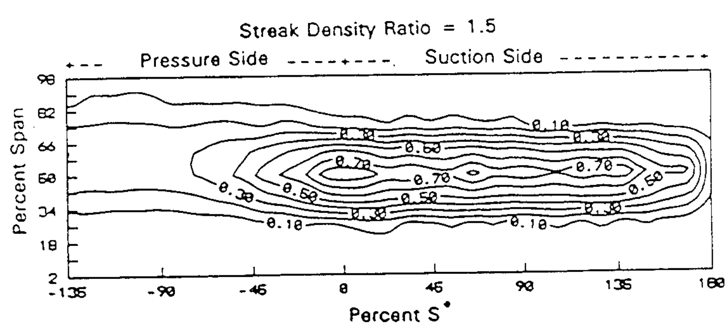
Effect of Reynolds Number on the Rotor Heat Transfer, Design Flow Coefficient, Grid Out





Hot and cold streak rectification in a rotor passage can produce significantly different recovery temperatures on the suction and pressure surfaces ($\Delta T \approx 100$ F°).

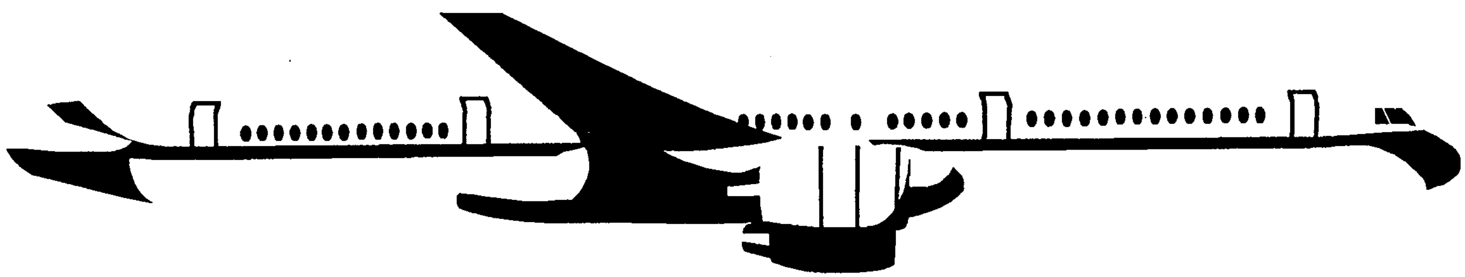




"Inherent Nonsteadiness" considerations include, but are not limited to, the following:

- Axial gaps in the range of 10% to 60% of airfoil axial chord
- Time average issues: performance and heat load
- Structural issues: unsteady forces (gust response)
- Potential flow interaction
- Wake interaction
- Rectification of streaks and wakes (Phantom Cooling)
- Boundary layer transition
- Secondary flow and tip leakage vortex interaction (3D flows)
- Deterministic stresses for an "average passage"
- Random and periodic contributions to total unsteadiness
- Stator-rotor shock interaction
- Intercomponent interactions (Combustor-Turbine-EGV)
-
-

CONTROL OF STREAM TURBULENCE IN GAS TURBINE ENGINES



DENNIS M BUSHNELL

NASA-LANGLEY RESEARCH CENTER

SOURCES OF UNSTEADINESS/ TURB.

- Wakes(Stator/Rotor)
- Inlet Distortion/Turbulence(Into Engine)
- Potential Flow Field/Shock Interactions
- Interference/Intersection Vortices
- Combustor/Combustion Processes
- Rotating Stall/Surge

TYPICAL LEVELS OF LOCAL STREAM TURB./UNSTEADINESS ARE O(5% TO 10% PLUS)

MAJOR ISSUES REGARDING GTE UNSTEADINESS/TURB.

- -MODES(Vel./Press./Temp.)
- -ORGANIZATION(Long./Horshoe/Transverse Vortices,Anisotropy,Episodic Nature(space and time))
- -FREQ. CONTENT/SCALE
- -DECAY RATE/PROCESSES(Adj. Surf. Effects & Flow Field Interactions)

STREAM UNSTEADINESS INFLUENCES IN GTE'S

- Comp./Turbine Blade
  - -intersection regions
  - -transition locus
  - -Cf/Qw/cooling effectiveness
  - -separation behavior
  - -shock/b.l. interac.
  - -fatigue/noise/vibration
- Combustor Eff./Fatigue/deposits/NOX
- Jet Acoustics

UNSTEADINESS WITHIN GTE'S

• SOURCE	incident flow	gen.locally
• SCALE	lg. scale(spatial & temporal,incl. shock waves	turbulence(wake /combustor flow
• SURFACES	rigid	aeroelas./flex.
• OPERATION	on design	off design

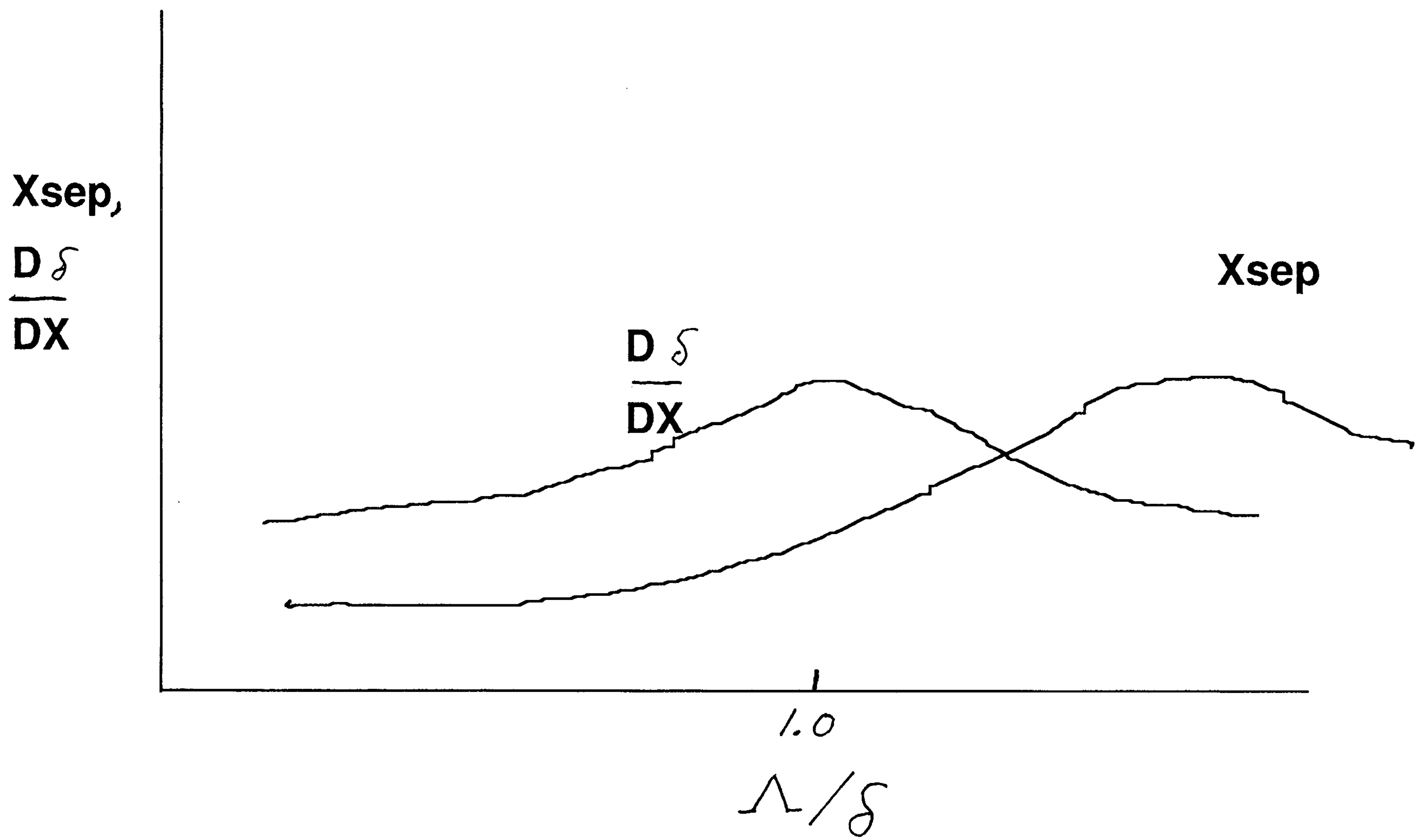
INFLUENCES OF STREAM TURBULENCE (GTE case mod. by swirl/curv)

• Transition	Enhancing
• Cf/Qw	Enhancing
• Flow Sep.	Retarding
• Free Mixing	Enhancing
• Acoustics/fatigue	Enhancing
• Vortex Lift	Retarding
• Combustion	Enhancing
• Flow Curv. Effects	Can Elim. Steady Gortler Vortices

THE EFFECT(S) OF STREAM TURBULENCE CHANGES FROM BODILY CONVECTION TO DIRECT INTERFERENCE WITH EDDY PROCESSES WHEN THE SHEAR LAYER THICKNESS GROWS TO THE SAME ORDER AS THE STREAM TURBULENCE LENGTH SCALE

P. BRADSHAW,

INFLUENCE OF STREAM TURB. SCALE



"There Is A Critical Degree Of (Stream)Turbulence Where The Boundary Layer Becomes Turbulent Without Separation,Then The Cascade Performance Has An OPTIMUM"

R.Kiock

Agard AG 164,1972

- OVERALL Effect(Of Stream Turb.) Is Usually A DECREASE In Compressor LOSS

  -Schlichting & Das,Evans

- "The Total Pressure LOSS Coefficient In A Cascade DECREASES With INCREASE Of Free Stream TURBULENCE"

  -S.Absar,1988 [AFIT M.S. Thesis]

- "ADDITION Of Free Stream TURBULENCE REDUCES LOSS Through The (Compressor) CASCADE" -E.Poniatowski,1988,ibid

"Even Though The Losses At Midspan Increase Up To 30% Due To Early Onset Of Transition And The Unsteady Boundary Layer,OVERALL LOSSES For The ENTIRE PASSAGE DECREASE By Nearly 40%,CAUSED BY DECREASED CORNER SEPARATION"

-Schulz/Gallus,Agard C.P. 468,1990

SUGGESTION REGARDING GTE UNSTEADINESS/TURB.

- ALTER EFFECTIVE LENGTH SCALE,STRUCTURE,AMPLITUDE OF LOCAL STREAM DYNAMICS TO EVEN FURTHER REDUCE;

  -SEPARATION

  -SECONDARY FLOW LOSSES

  -NOISE?

  AS WELL AS:

  -IMPROVE COMBUSTOR EFFICIENCY,REDUCE DEPOSITS/NOX

PROSPECTIVE TECHNIQUES TO ALTER STREAM DYNAMICS

- SERRATED TRAILING EDGES(Reduces Separation,Enhances Wake Mixing/Reduces Wake Turb. Scale?)-T.E. “crenulations” red. total cascade press. losses in AFIT/DECOOK research(‘91)
- (steady/Dyn.) Wake/Localized Injection
- Permeability/Passive Bleed
- Imbedded Globally Unstable Flows/Edge Tones
- Engine Design Details (e.g.axial clearances,blade loading,solidity,passage flow curvature(s), transverse pressure gradients,combustor/combustion dynamics, etc.)

Major Issues-Stream Turb./ Unsteadiness in GTE'S

- WHAT DYNAMICS IS PRESENT IN LOCAL STREAM FLOWS OF "REAL ENGINES" AND WHAT ARE ITS SOURCE(S)
- WHAT DOES THIS DYNAMICS DO TO ENGINE EFFICIENCY/OPERABILITY
- HOW CAN THIS DYNAMICS BE CHANGED/ CONTROLLED TO IMPROVE ENGINE FIGURES OF MERIT

[INCLUDING(OBVIOUSLY) EFFECTS OF ROTATION]

UNSTEADY PHENOMENA IN TURBINES

by

Professor A.H. Epstein
Gas Turbine Laboratory
Massachusetts Institute of Technology
Cambridge, MA 02139

Presented at

WINCAT

October 1993

WHY DO WE CARE ABOUT UNSTEADINESS?

- To get the physics correct, leading to
- Accurate physical models for
  - Turbine design
  - Analysis
  - Measurement design
  - Data analysis
- Implications for
  - Aerodynamic performance (efficiency and flow)
  - Heat transfer (predicting wall temps., optimizing cooling flows)
  - Turbine life

HOW MUCH ACCURACY IS NEEDED IN TURBINE DESIGN?

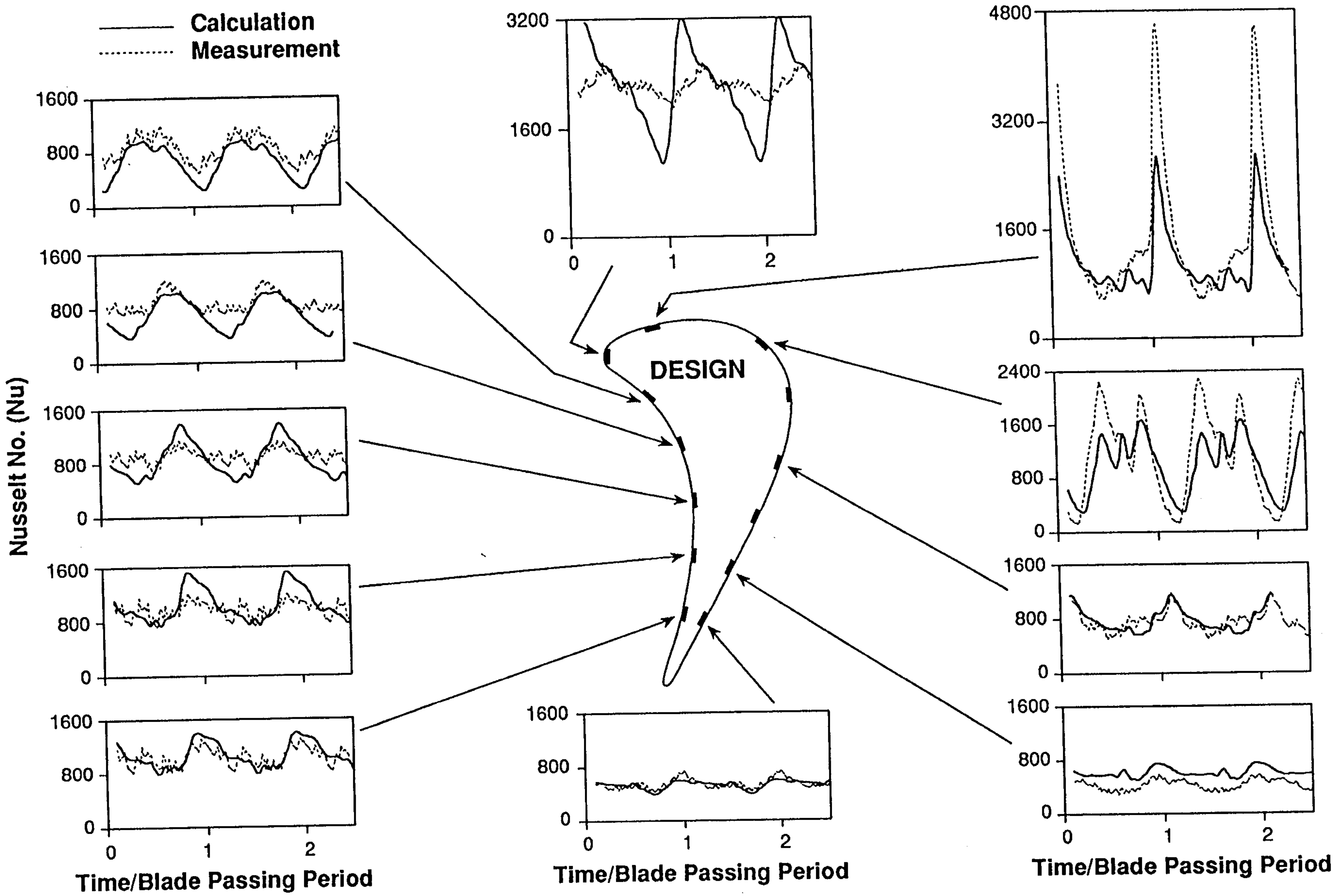
Variation	1st Blade Creep Fatigue Life	1st Blade Oxidation Life
Local gas temp. ±20°R (Mean of 3500°R)	±15%	±14%
Centrifugal stress ±1%	±6%	—
Metal temp. ±5°R (Mean of 1800°R)	±8%	±8%

71

NEW TECHNOLOGIES MAKE DETAILED STUDY POSSIBLE

- Fully-scaled short duration rotating rigs
- High frequency response instrumentation
  - Heat flux, temperature, pressure, Mach No.
- Optical flow diagnostics
  - Gas and wall temperatures, velocity
- 2-D and 3-D unsteady CFD
  - Euler codes
  - Thin shear layer codes
  - N.S. codes

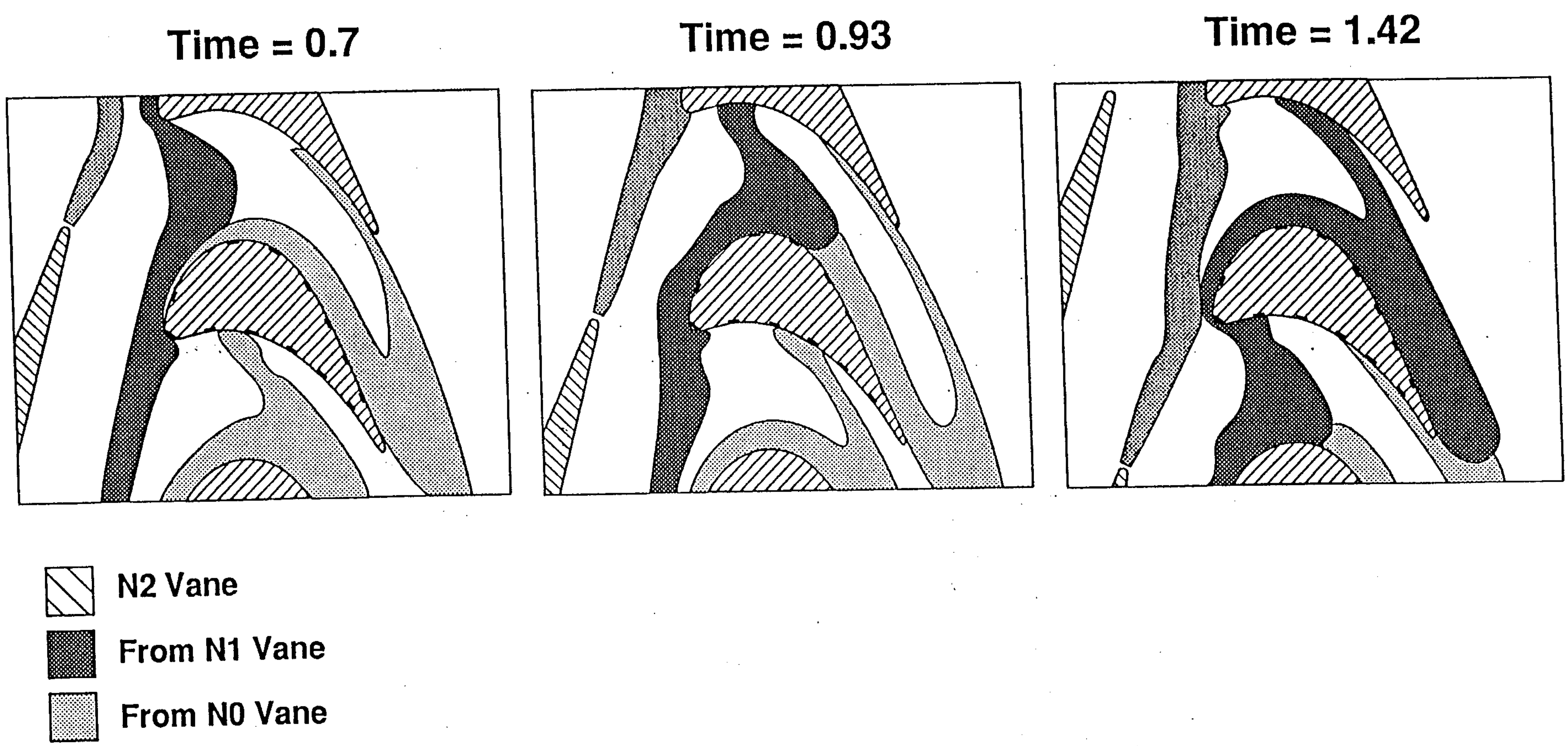
ROTOR HEAT TRANSFER IS FUNDAMENTALLY UNSTEADY
(Uncooled Transonic Rotor Blade)



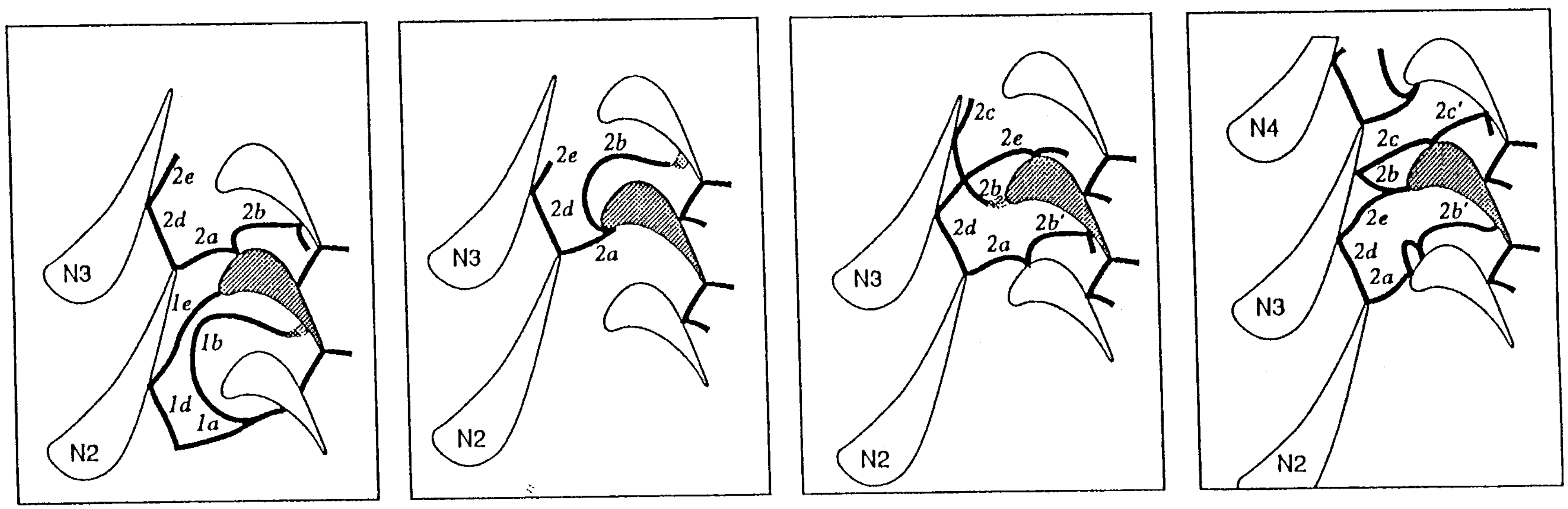
SOURCES OF UNSTEADINESS

- Vane-blade interactions
  - Wakes
  - Potential disturbances (shock waves, etc.)
  - Tip vortices
- Nonuniform geometries
- Inflow nonuniformity and secondary flows
- Inherent flow instabilities
- Cooling flow fluctuations
  - Driven by external flow unsteadiness

VANE WAKE INTERACTION

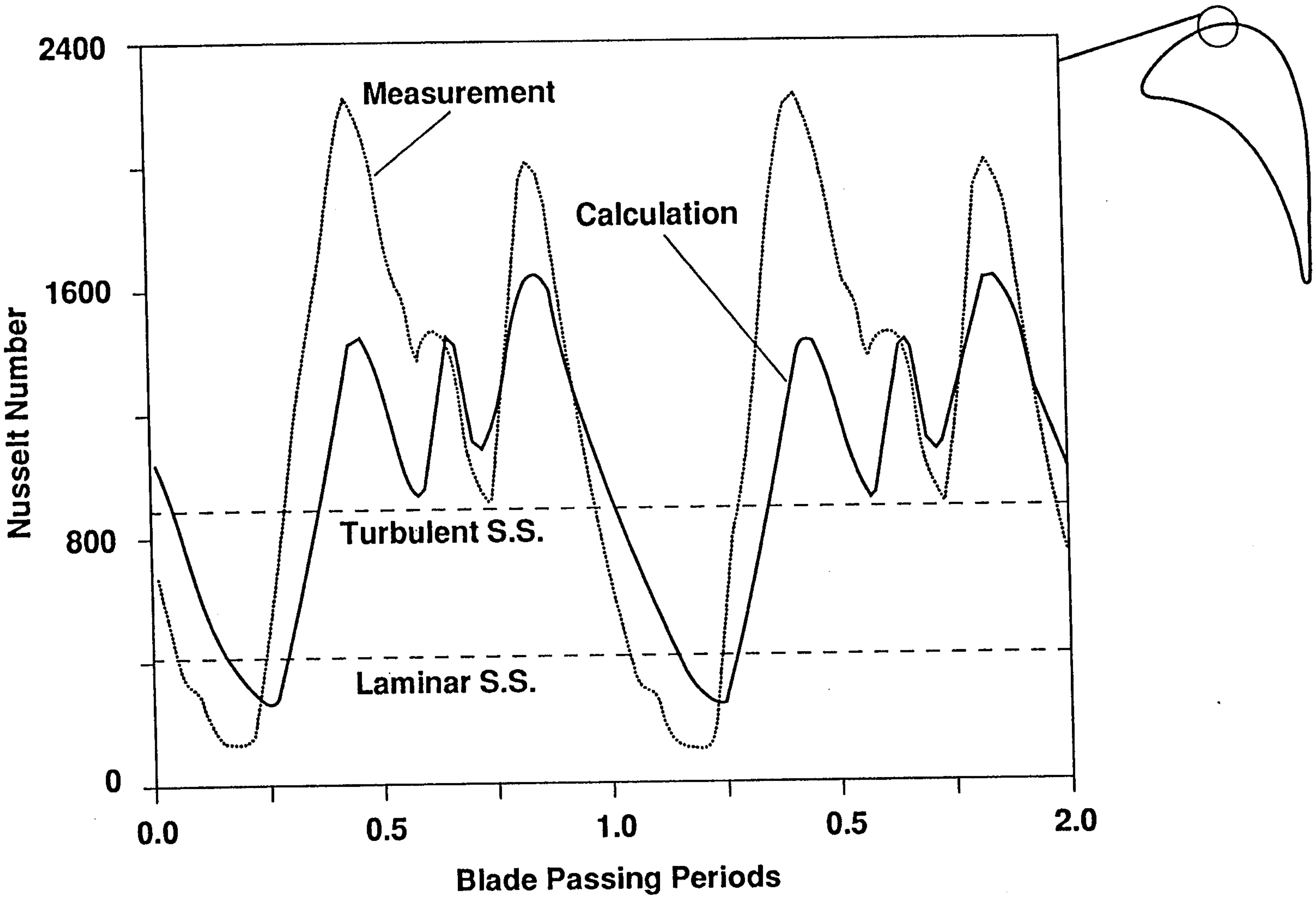


PREDICTED SHOCK STRUCTURE



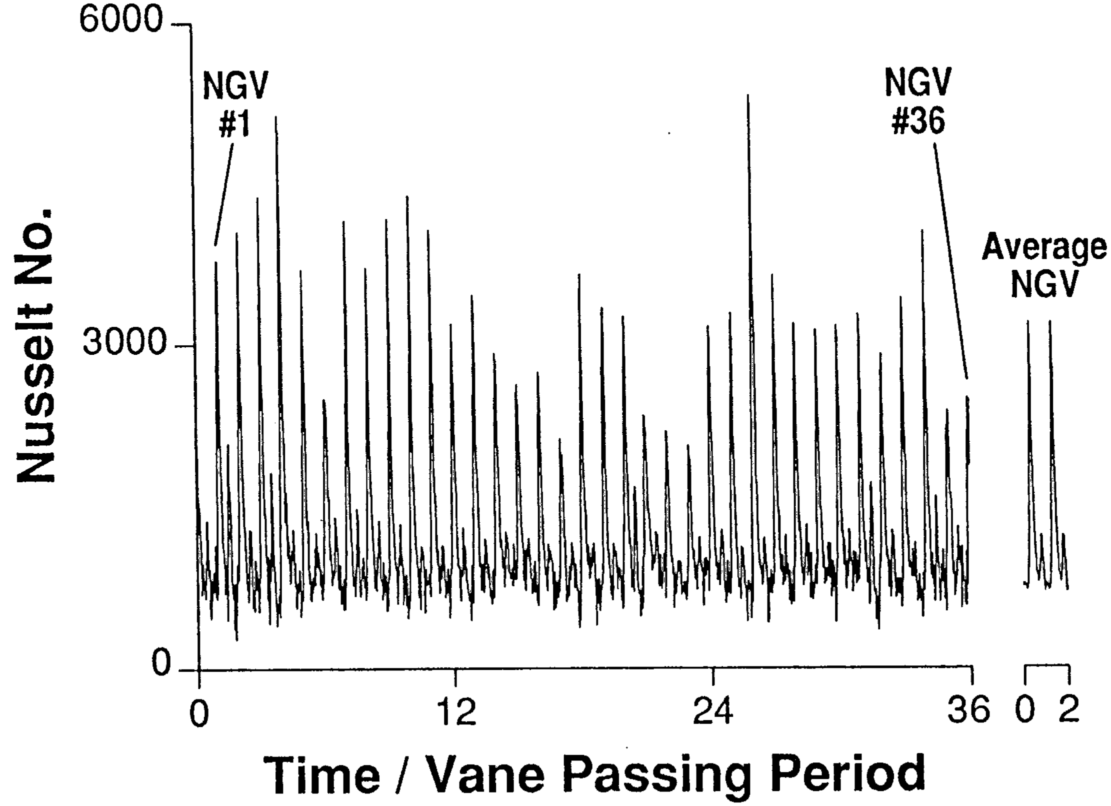
Time = 0.82 Time = 1.11 Time = 1.37 Time = 1.6

TIME-RESOLVED FLOW IS NOT QUASI-STEADY



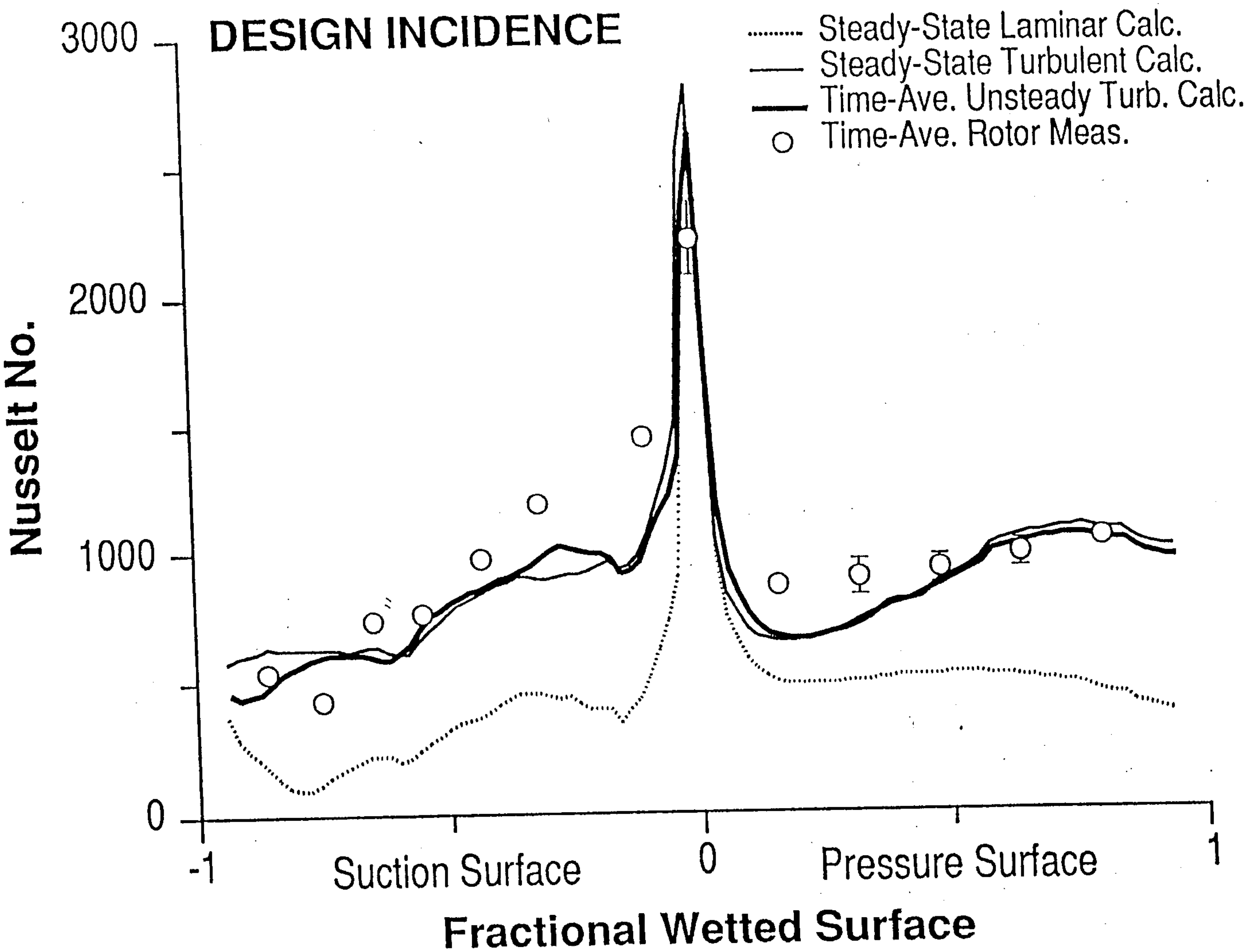
GEOMETRIC NONUNIFORMITIES INTRODUCE UNSTEADINESS

– Crown of Suction Surface -

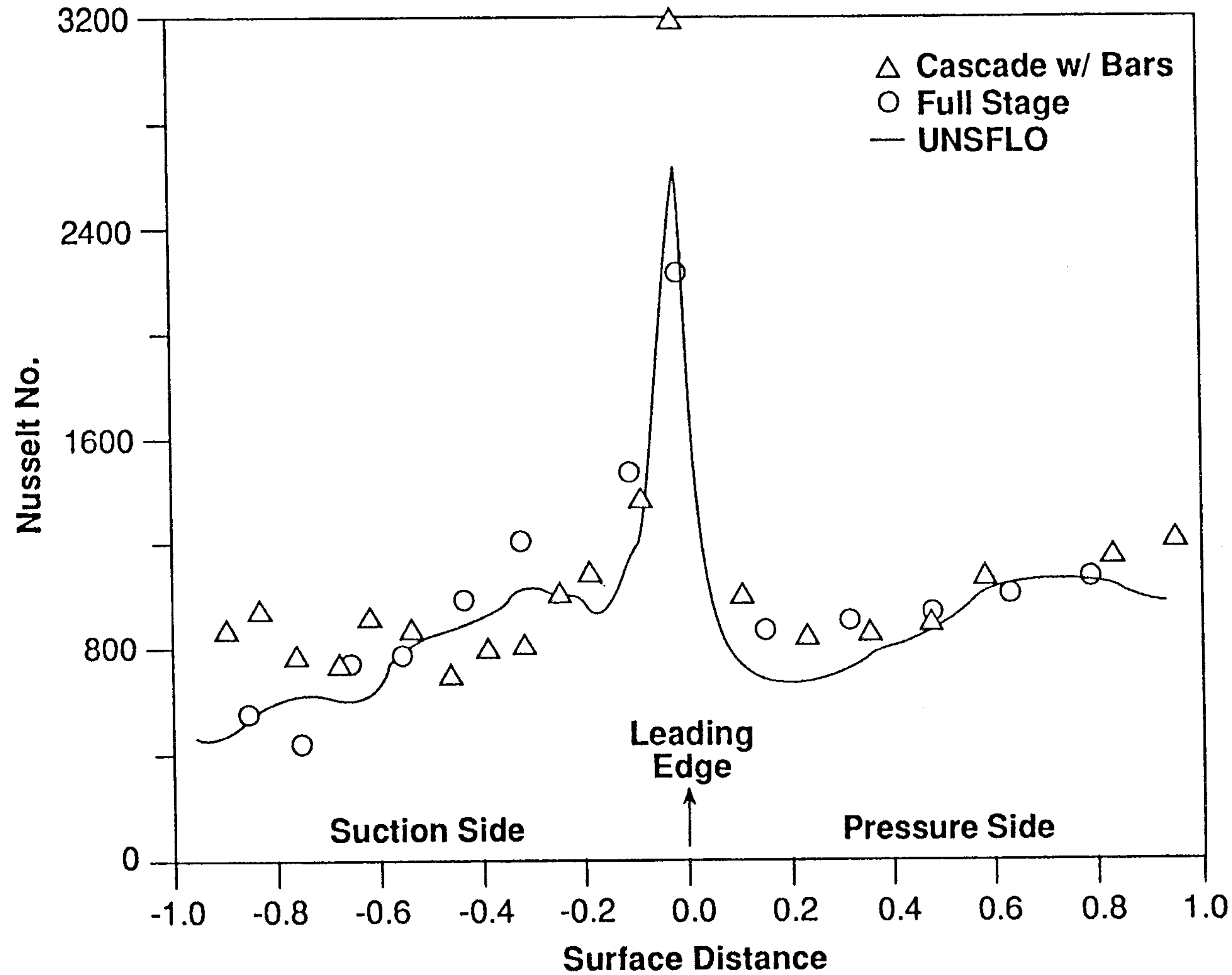


- Variations consistent with 2% NGV geometry variation

AVERAGE HEAT FLUX ABOUT ROTOR



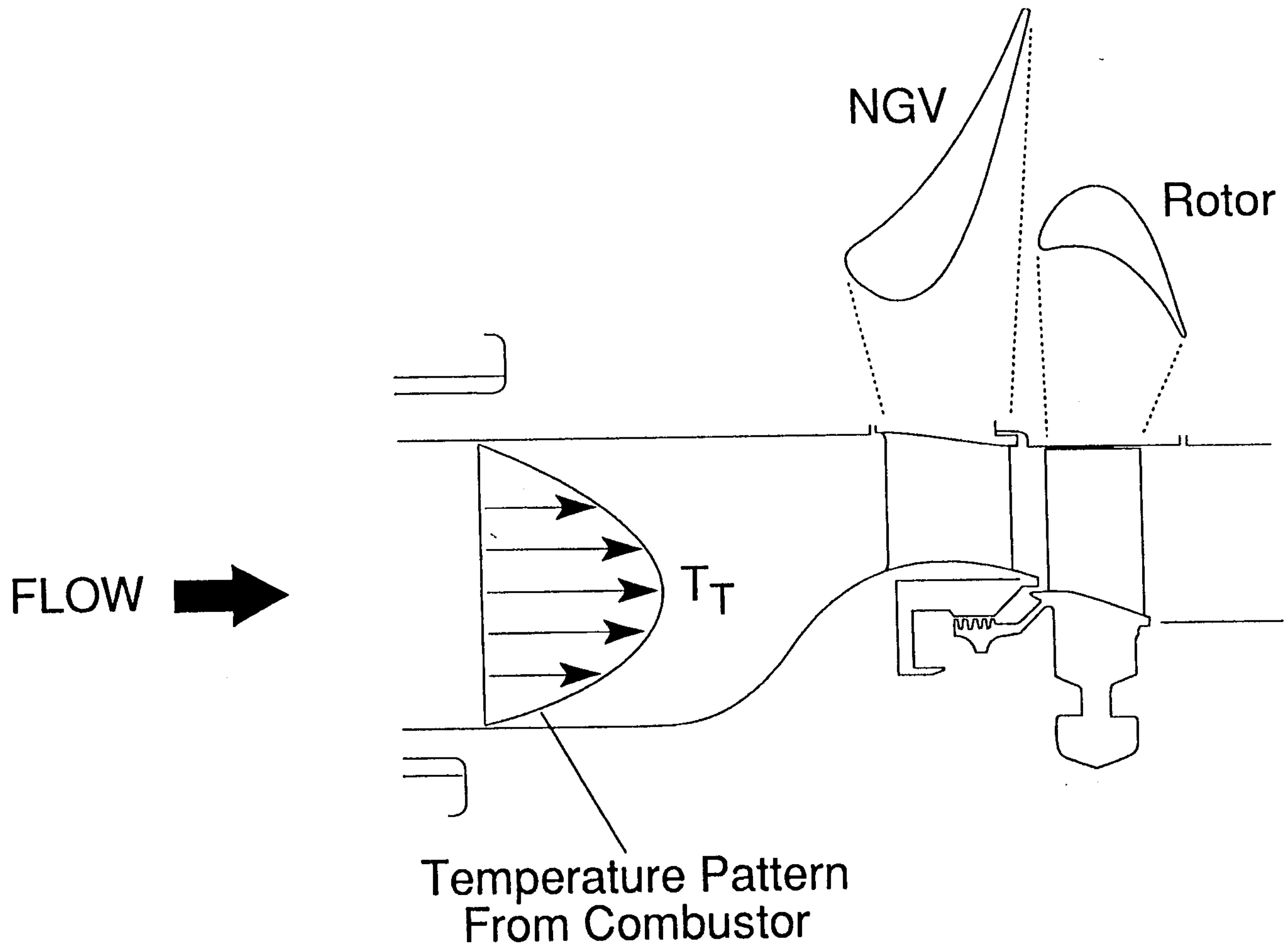
HIGH SPEED ROTATING RIG RESULTS MATCH CASCADE



- Thus:
  - Blade row interactions
  - 3-D flow geometry
  - Rotation

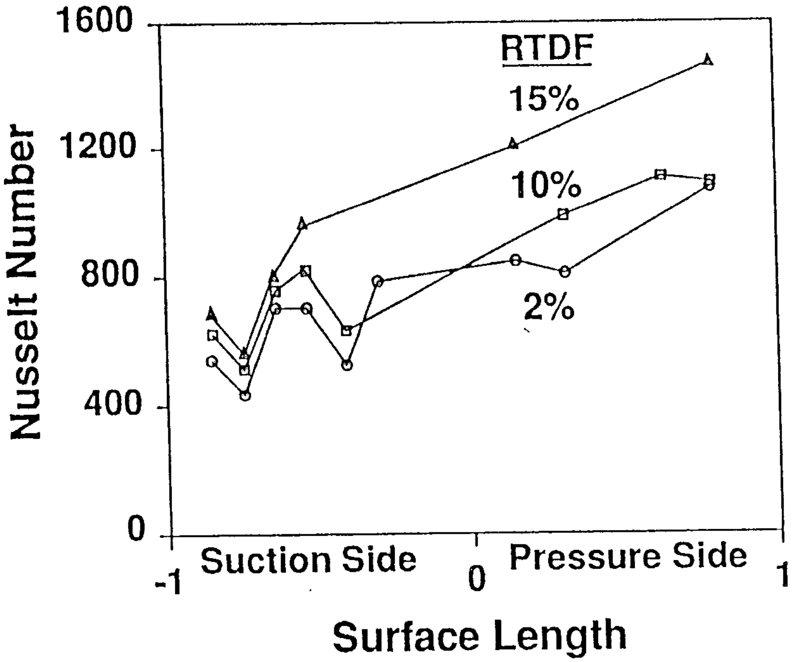
  are not only key to engine problem

INLET TEMPERATURE DISTORTIONS HAVE STRONG INFLUENCE

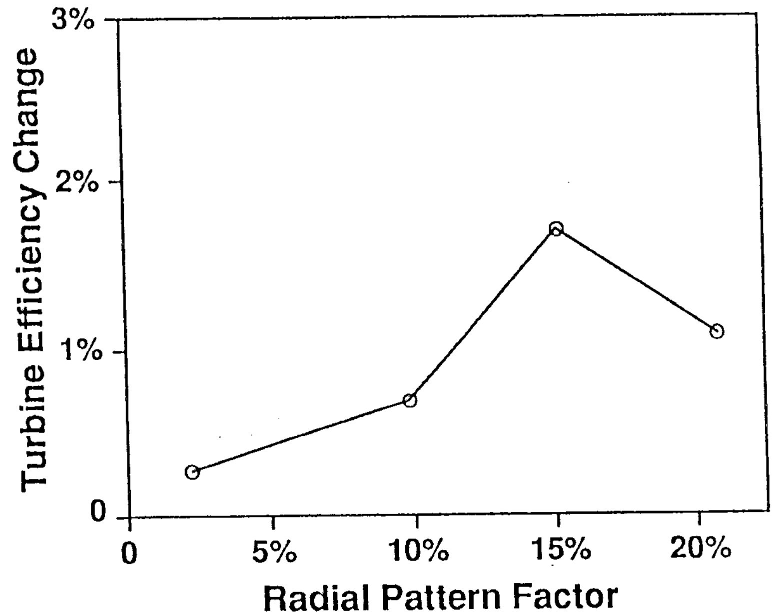


COMBUSTOR PATTERN FACTOR MAY BE KEY DRIVER

Heat Transfer



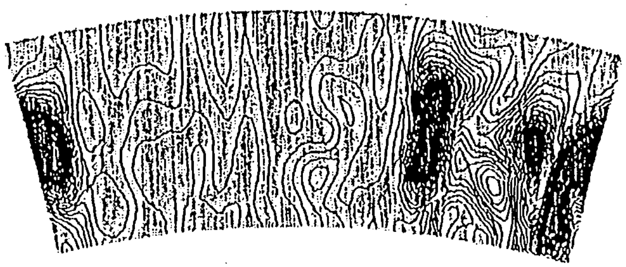
Efficiency



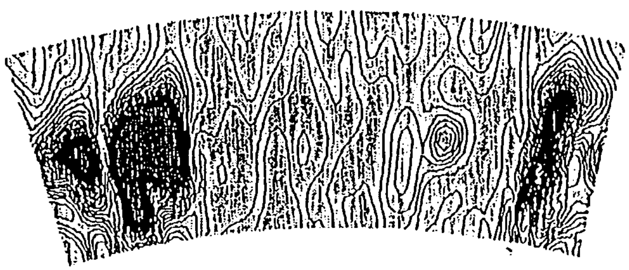
ROTOR EXIT TOTAL TEMPERATURE FROM 3-D EULER CODE

<u>Time</u>

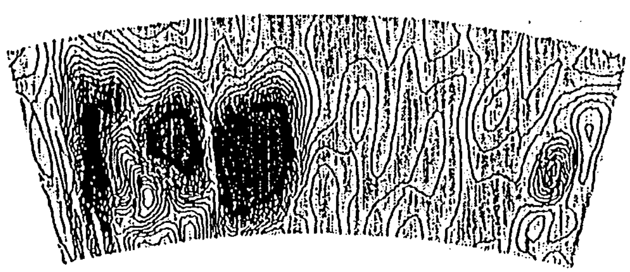
0.0



0.167



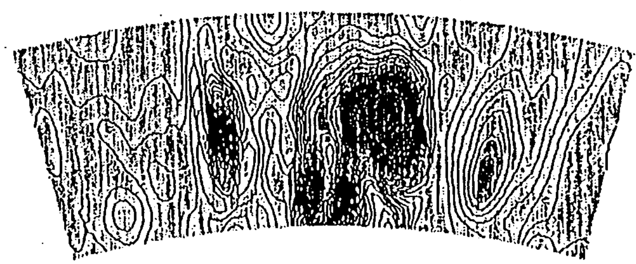
0.333



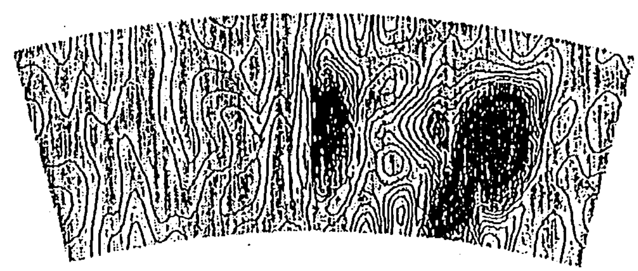
<u>Time</u>

0.5

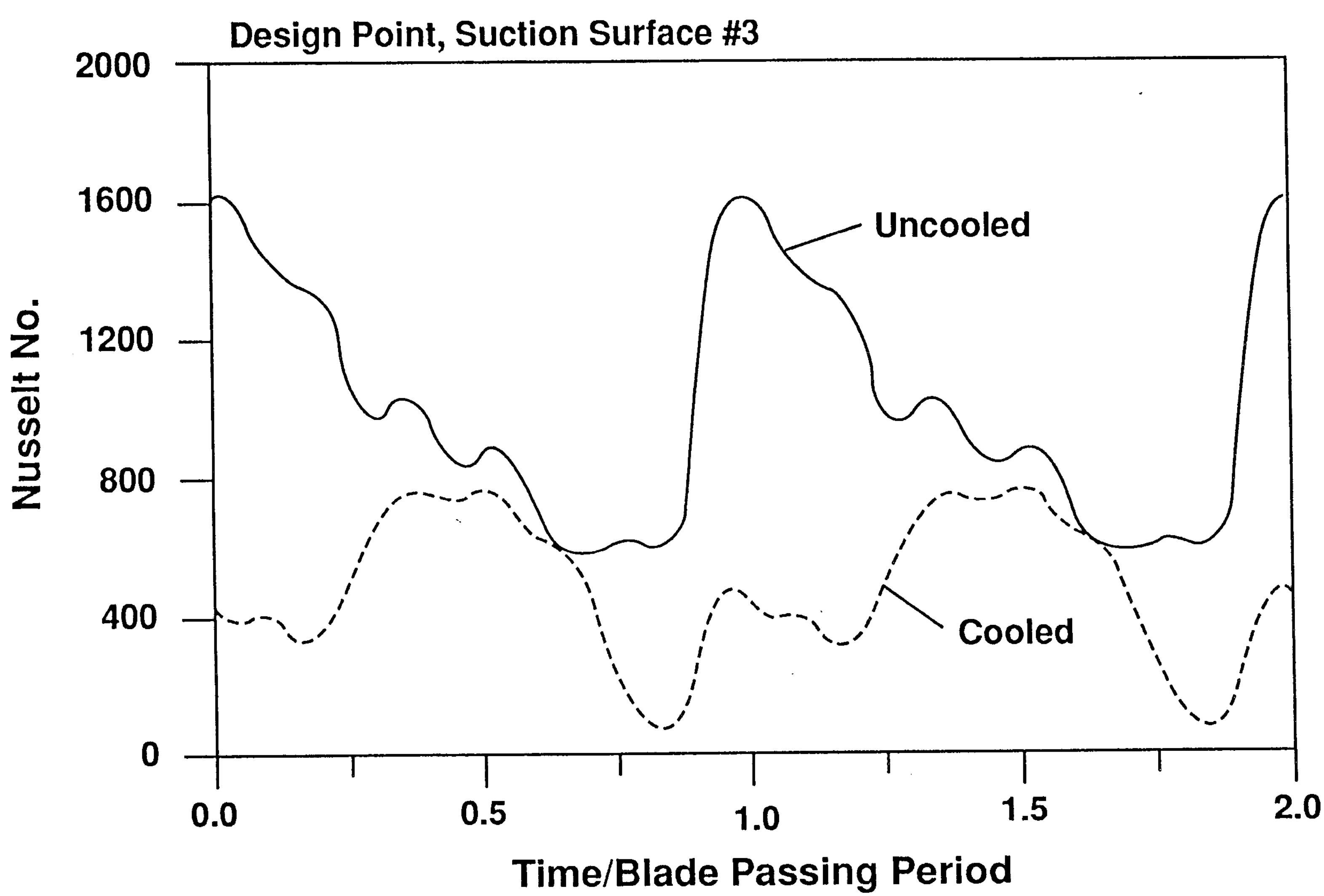
0.667



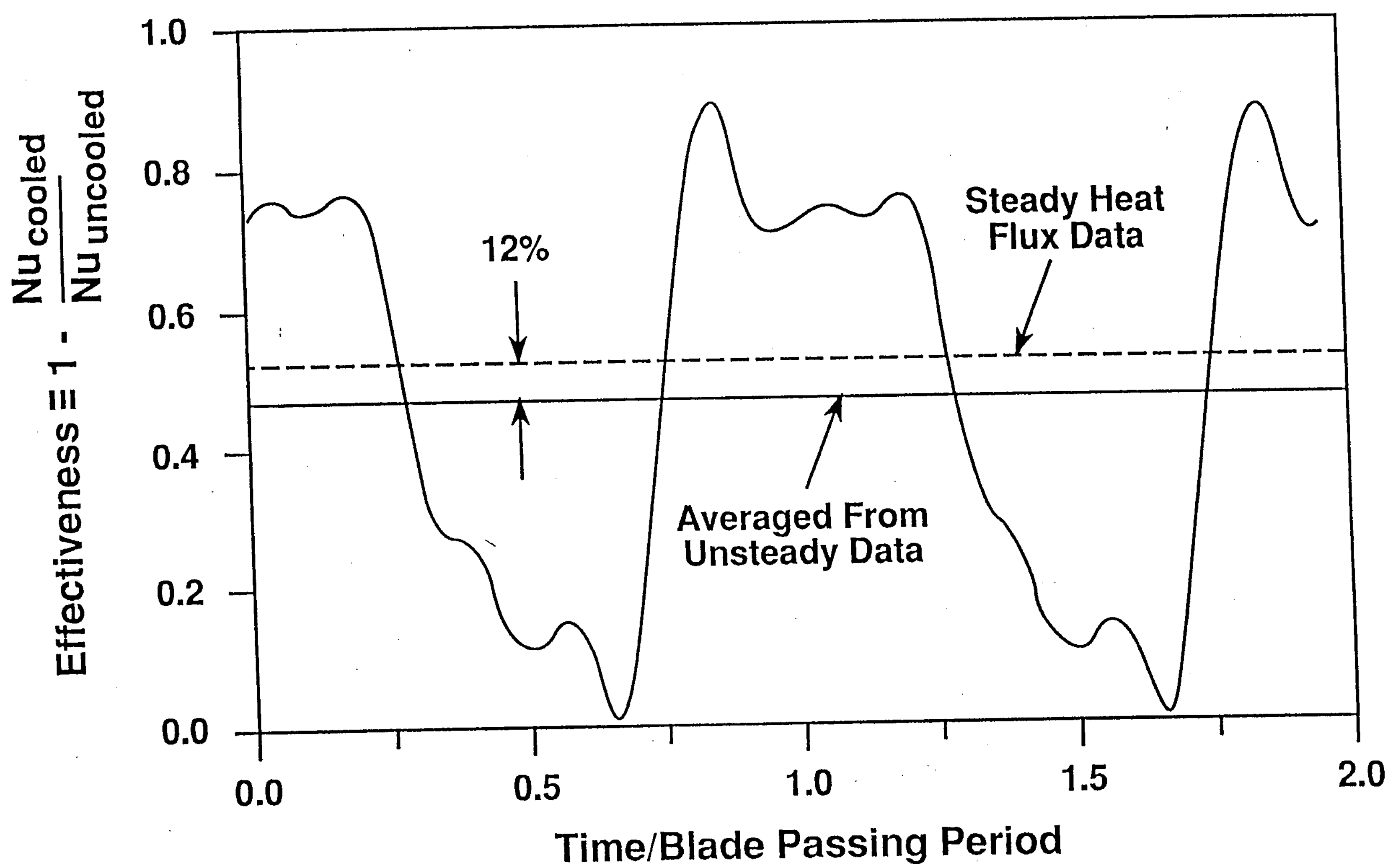
0.833



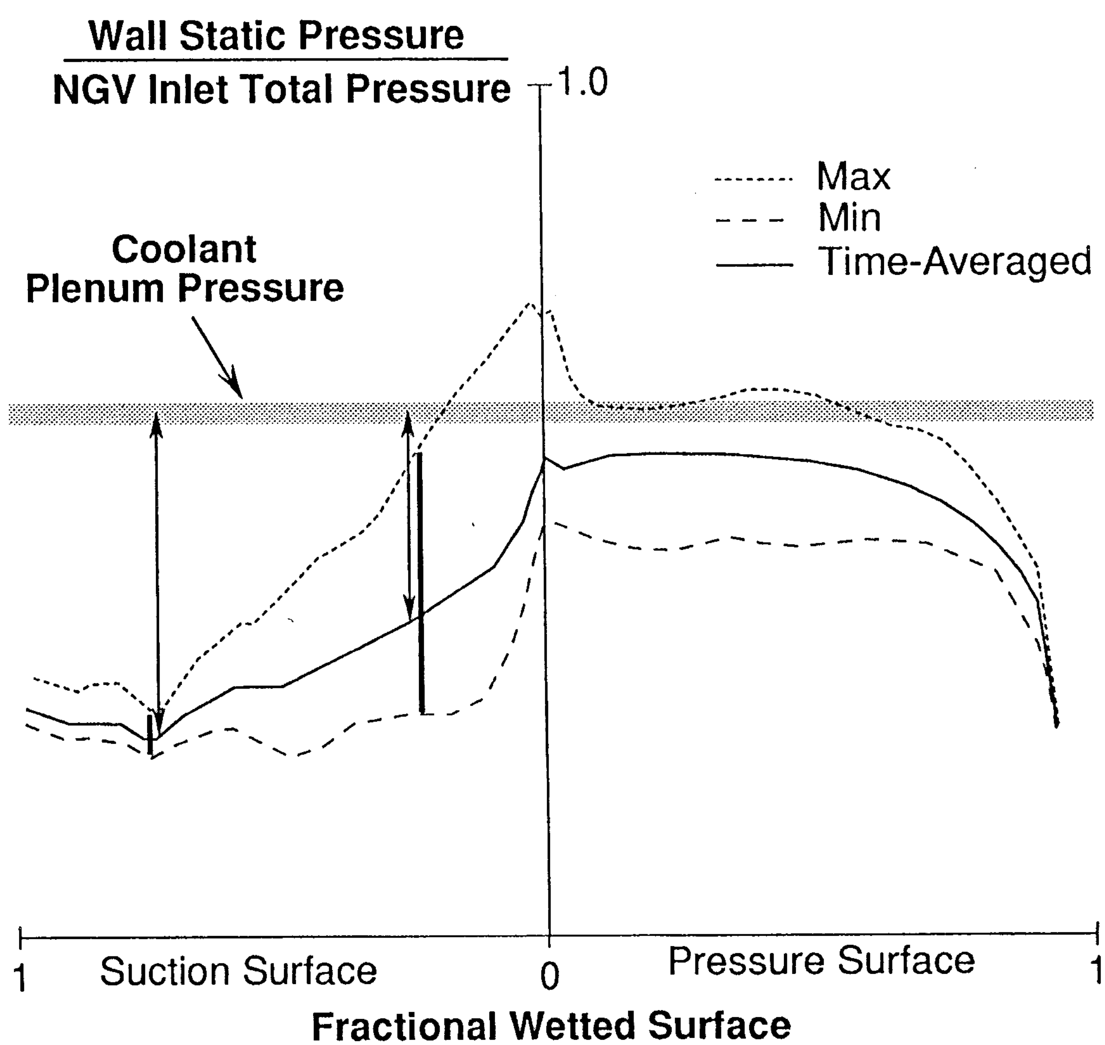
UNSTEADINESS INFLUENCES BLADE COOLING



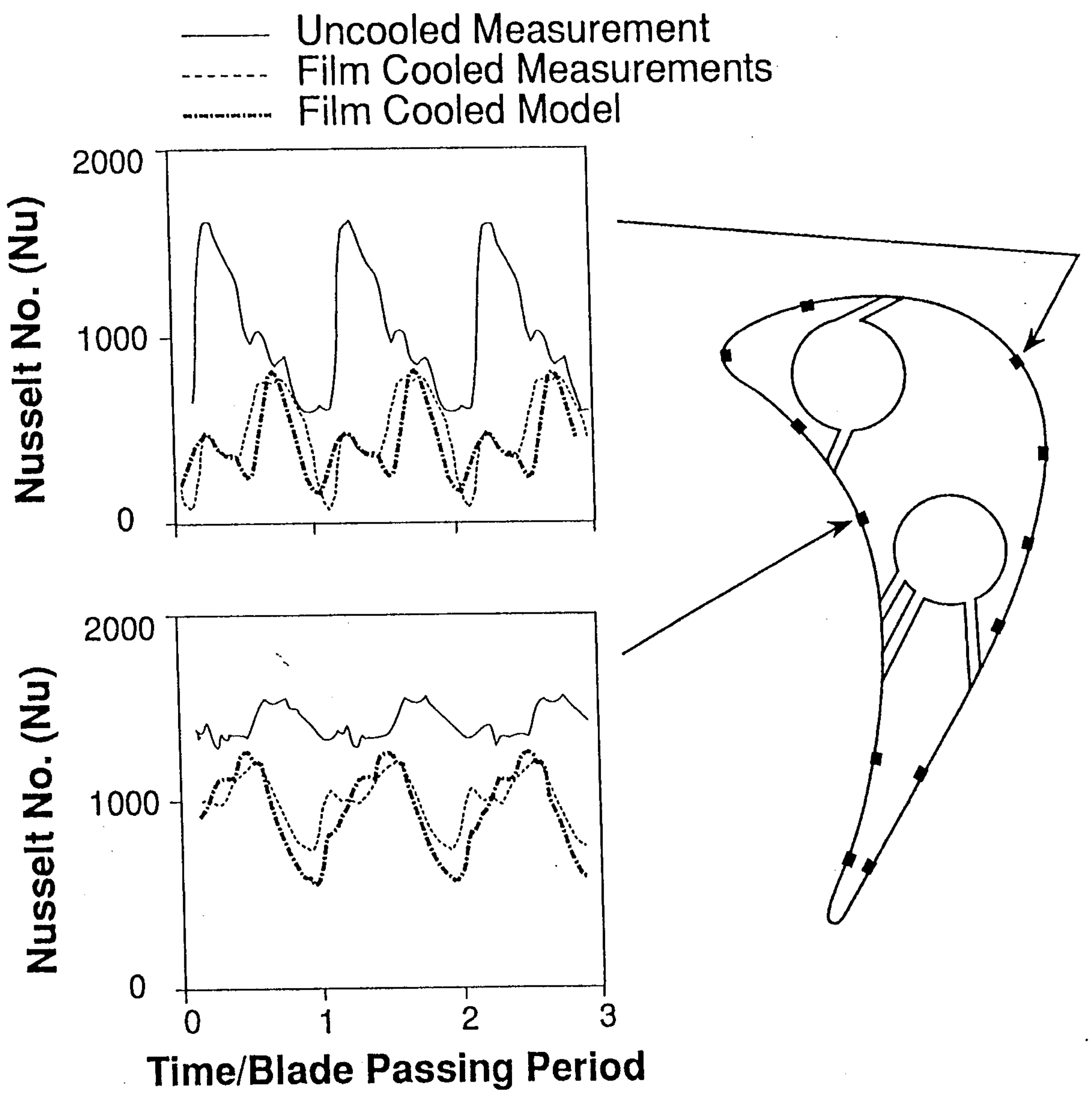
UNSTEADINESS INFLUENCES COOLING PROCESS



COOLANT DRIVING PRESSURE IS UNSTEADY



UNSTEADY BLOWING IMPORTANT TO FILM COOLING



DESIGN ISSUES AND GOALS FOR ADVANCED TURBINES

- Aero performance
  - Increase turbine efficiency by exploiting 3-D and unsteady nature of the flow
  - Desensitize turbine performance to rotor tip clearance
  - Improve coolant/main flow interactions
  - Raise performance at low Reynolds No.'s (<150,000)
- Cooling and life
  - Improve heat load prediction
  - Aerodynamic design for low heat load
  - Improve cooling on rotor pressure surfaces
  - Optimize unsteady cooling processes
- Aeromechanical
  - Improve prediction of both aero and mechanical damping

RESEARCH ISSUES FOR ADVANCED TURBINES

- Multiple blade row interacctions (2 rows and 3 rows or more)
- Combustor inflow nonuniformities
  - Long length scale (hot streaks, radial distortion)
  - Short length scales (combustor thermal turbulence)
- Tip flows (clearance vortices, etc.)
- What is an appropriate boundary layer model(s) for turbines?
  - Strongly forced boundary layers
  - Reynolds No.'s can be transitional (<200,000)
- Unsteady turbine cooling interactions
  - Main flow/film cooling/unsteady blowing
  - Unsteady main flow influence on internal cooling
- Aero and mechanical damping
  - How to predict them
  - How to measure them

UNSTEADY FLOW IN TURBINES

WRIGHT LABORATORIES
AERO PROPULSION AND POWER DIRECTORATE

R. B. RIVIR

Purdue / AFOSR / 93

SUMMARY
NASA WORKSHOP ON UNSTEADY FLOW IN TURBOMACHINES

- WHAT AREAS SHOW POTENTIAL
  - BLADE PASSAGE - INCREASE PEAK STAGE LOADING / VANE ROTOR SPACING, Le~Pitch
  - STABILITY - SURGE STALL MARGINS
  - AEROELASTIC RESPONSE - HIGH CYCLE FATIGUE
  - TRANSITION - TRANSITION LOCATION, SMALL Le
- WHAT ARE THE MAGNITUDE OF THE GAINS EXPECTED
  - COMPRESSOR +1%, BLADE PASSAGE - INCREASE PEAK
  - TURBINE +2 - 4%, TRANSITION BEHAVIOR, LOCATION
    - LIFETIME & PERFORMANCE - HOT STREAK, DT=100 -700^{o}F
    - WAKE TRANSPORT - PHASE & HEAT TRANSFER*
- HOW CAN THESE GAINS BE IMPLEMENTED
  - CFD -CODE VERIFICATION
  - EXPERIMENT - TRANSITION AFFECTED BY THE "ROUTE TO Tu"

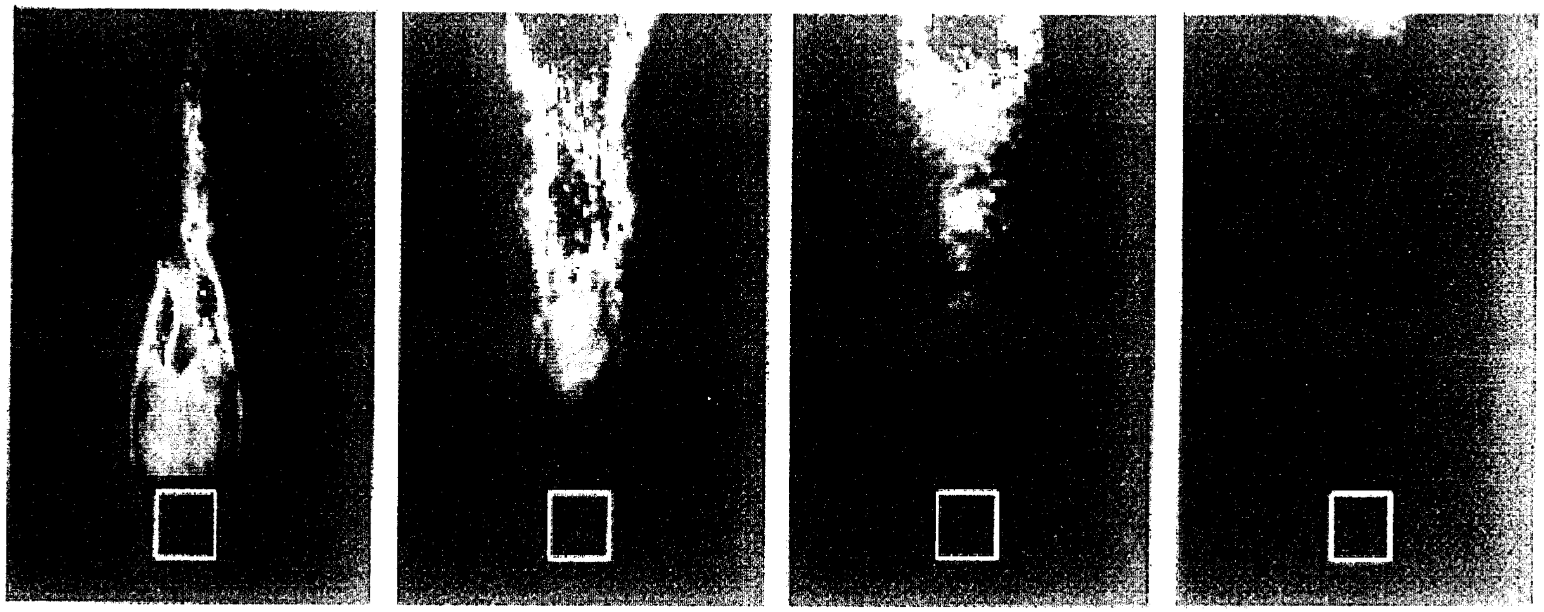
UNSTEADY / HIGH TURBULENCE HEAT TRANSFER

- **BRADSHAW & SIMONICH** $St/Sto=(5Tu/100+1)$
- **HANCOCK/BLAIR** $St-Sto/Sto=100\ Tu/(\alpha\beta)$
  - $\alpha=(L_e/\delta+2)$, $\beta=(3e^{-Reo/400}+1)$
- **MACIEJEWSKI** $St'=h/\rho u'c_p$
- **AMES** $St-Sto/Sto=Tu(\Delta_2/L_u)^{1/3}(R_{eh}/1000)^{0.25}$
  - $St''=St'(R_{eh}/250)^{0.25}$
- **MALAN & JOHNSTON** $St'''\sim R_{eo}^{\ 0.25}$

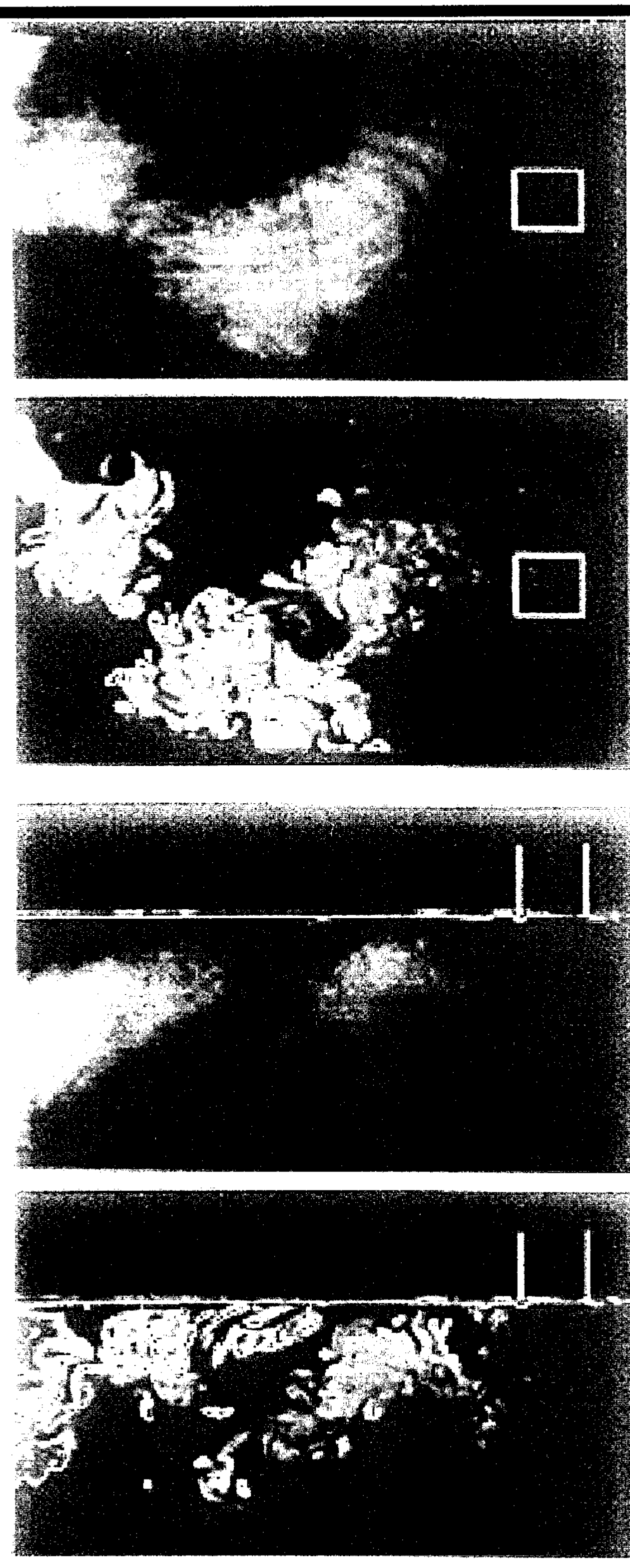
"MOST EXPERIMENTS ARE SIMILAR IN SCALE AND SIMILAR IN VELOCITY"
TURBULENT REYNOLDS NUMBER ~ CONSTANT

- BLADE VANE INTERACTION
    - CASCADE WITH ROTATING BARS
- UNSTEADY TEMPERATURE
- WALL JET
    - Tu SCALES
    - St'
- JETS IN CROSS FLOW
    - FORCED BOUNDARY LAYERS
    - FORCED CORE FLOW
- CHARACTERIZATION OF COMBUSTOR FLOWS

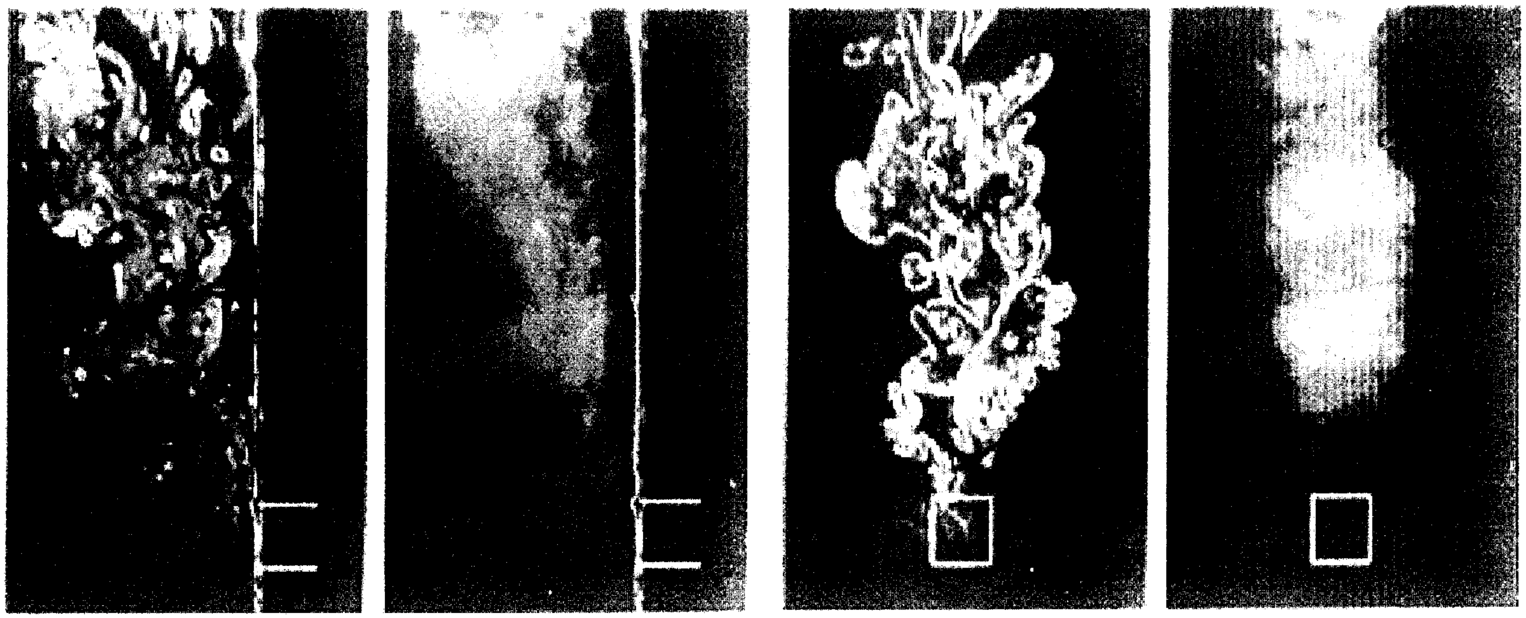
UNDRIVEN
90 DEG VIEWS AT 4 ELEVATIONS



1 cm 2 cm 3 cm 4 cm



DRIVEN ACTUATORS 3 & 4



CENTER

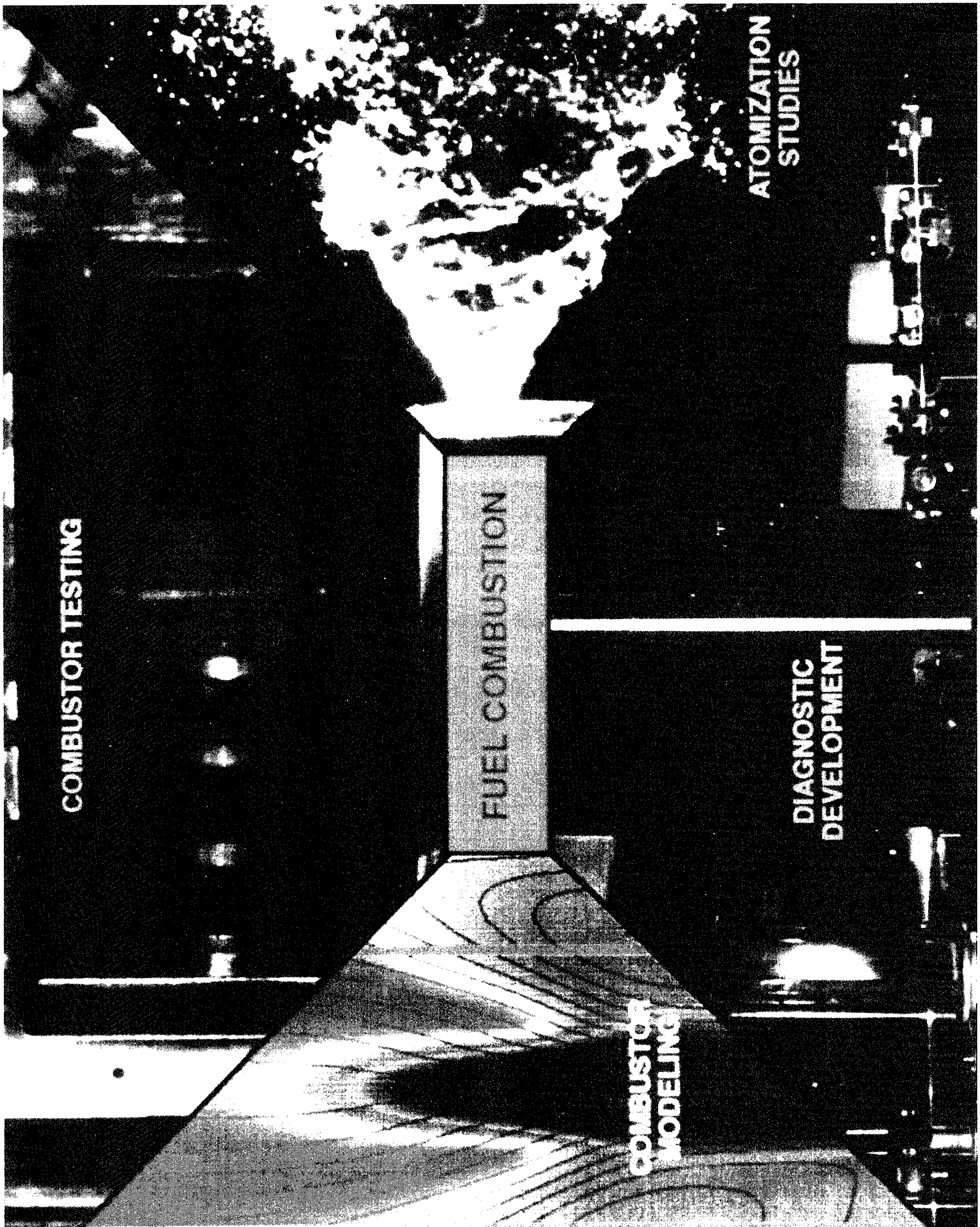
WINCAT WORKSHOP

NEW DIRECTIONS FOR GAS TURBINE COMBUSTORS

W. M. ROQUEMORE

AIR FORCE WRIGHT LABORATORY

AERO PROPULSION AND POWER DIRECTORATE


COMBUSTOR TESTING
FUEL COMBUSTION
ATOMIZATION STUDIES
DIAGNOSTIC DEVELOPMENT
COMBUSTOR MODELING

PROGRAM OBJECTIVES

ADVANCED DIAGNOSTICS

- Develop, Evaluate, and Utilize Advanced Diagnostic Techniques in Studies

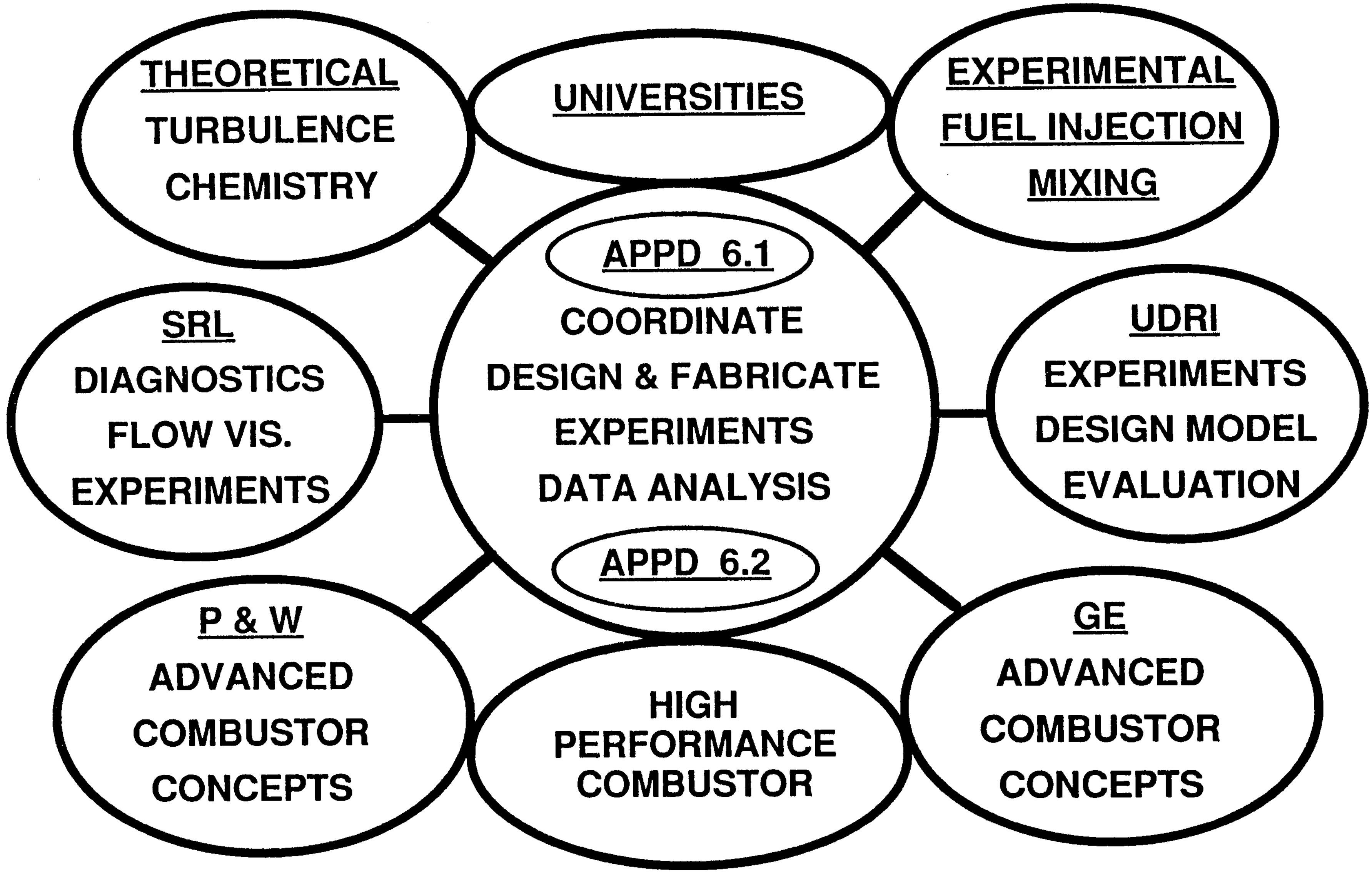
CFD COMBUSTOR DESIGN MODEL

- Aid Engine Companies in Developing and Evaluating Their Models
- Establish Data Base for Model Development and Evaluation
- Investigate Fundamental Physics and Chemistry Needed For Models

HIGH PERFORMANCE/LOW NOx COMBUSTORS

- Aid Engine Companies in Developing and Evaluating Advance Combustors
- Aid in Establishing Data Base for Staged Combustors
- Investigate Fundamental Physics and Chemistry of Mixing Processes

PROGRAM ORGANIZATION

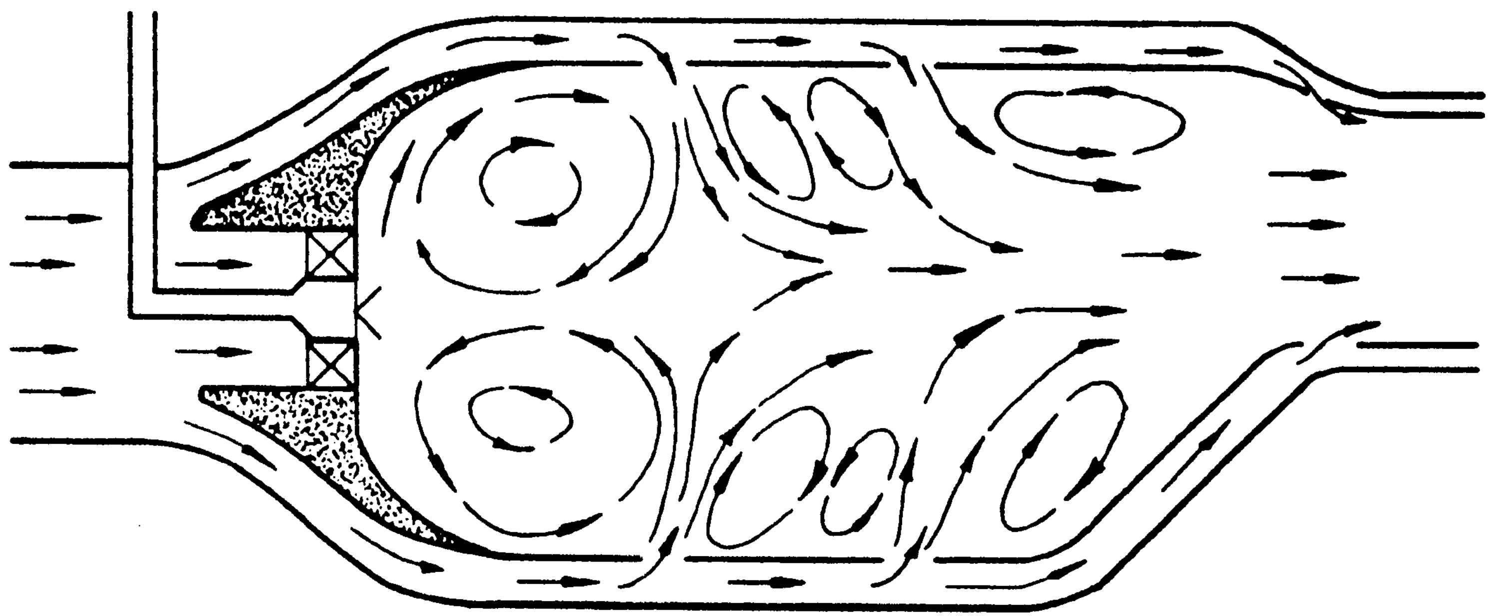


GAS TURBINE COMBUSTOR

FUEL SPRAY
- DROPLETTRAJECTORIES
- EVAPORATION

TURBULENCE
- TRANSPORT/MIXING
- BOUNDARYLAYER
- RECIRCULATION
- JETS
- SWIRL

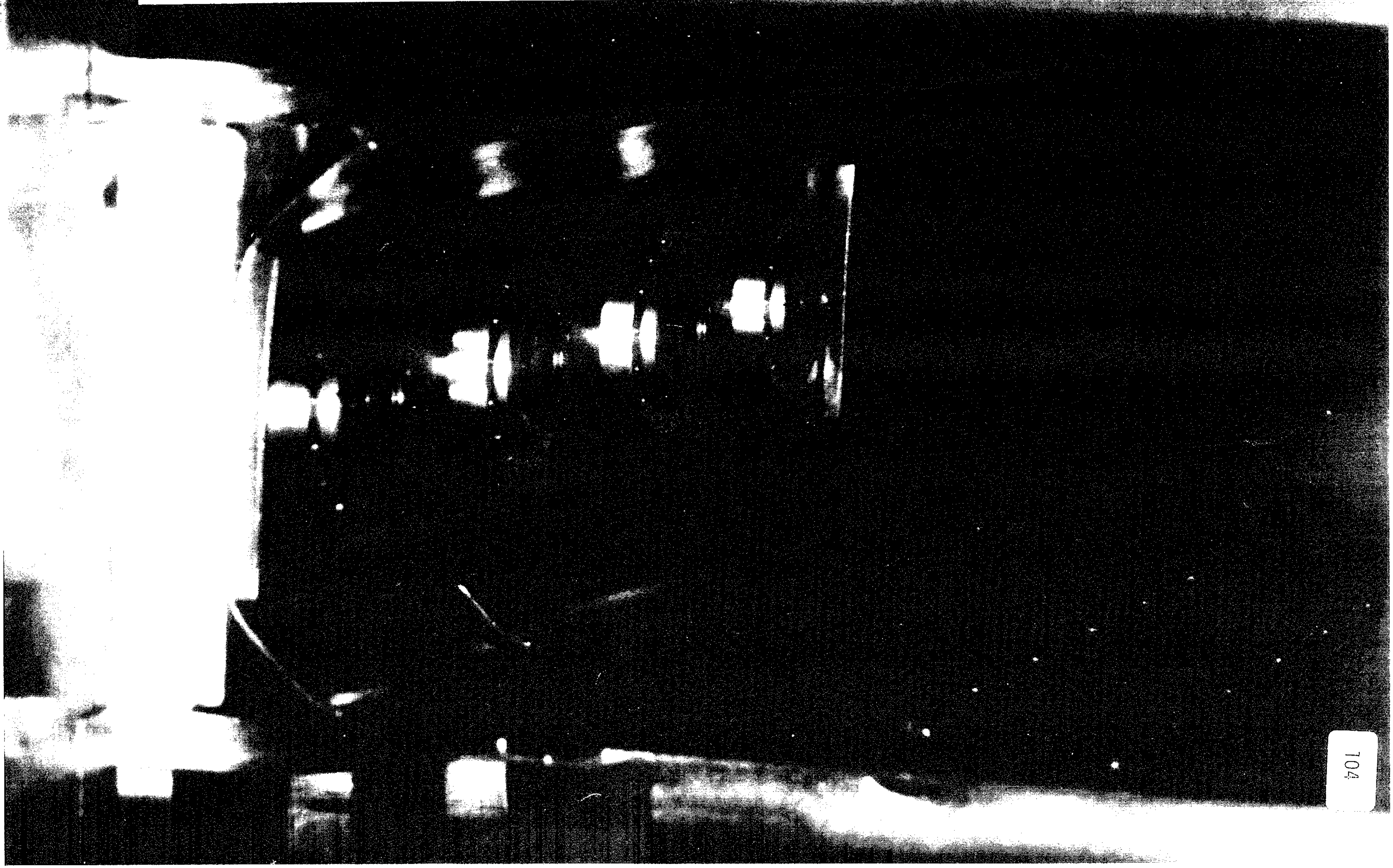
ACOUSTICS
- NOISE
- INSTABILITIES

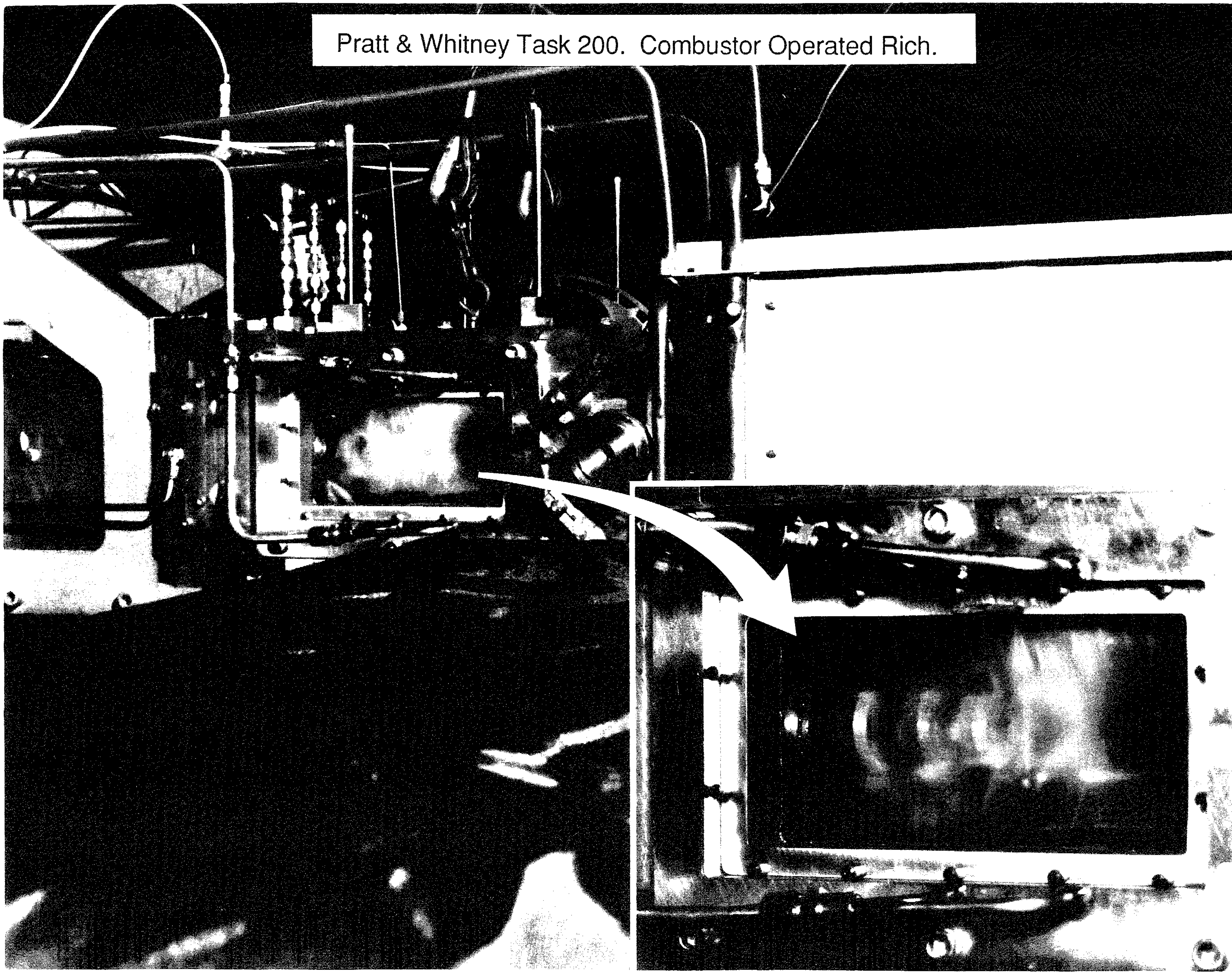


CHEMISTRY
- PYROLYSIS
- OXIDATION
- SOOT
- KINETICS

RADIATION
- SPECIES
- SOOT

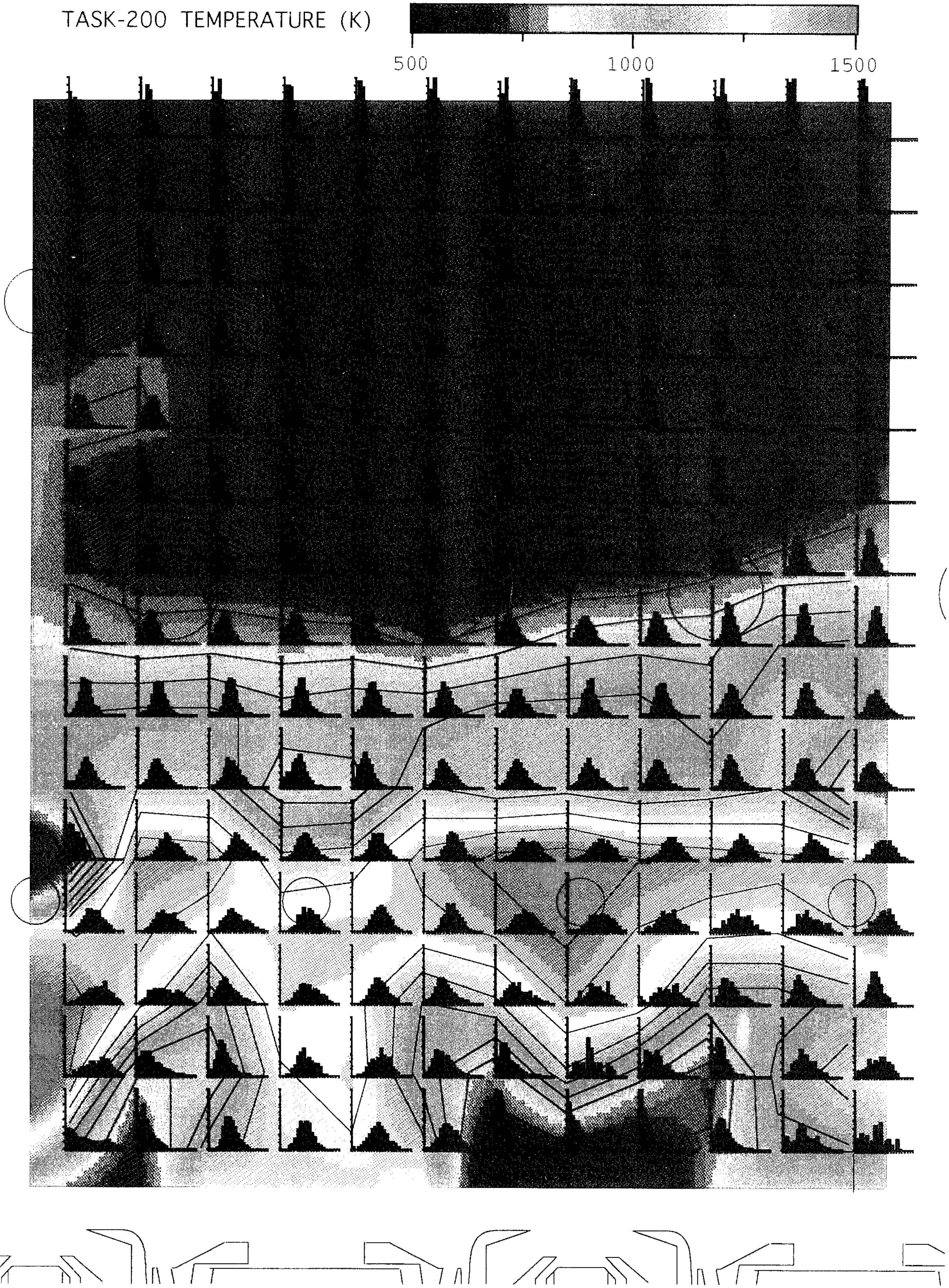
Pratt & Whitney Task 200 Research Combustor with Four Fuel Cups and Optical Access.





Pratt & Whitney Task 200. Combustor Operated Rich.

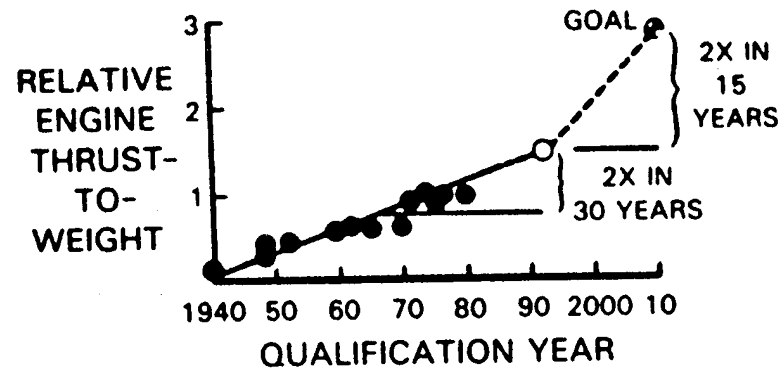
Temperature Contours and Probability Distribution Functions in Task 200 Combustor.

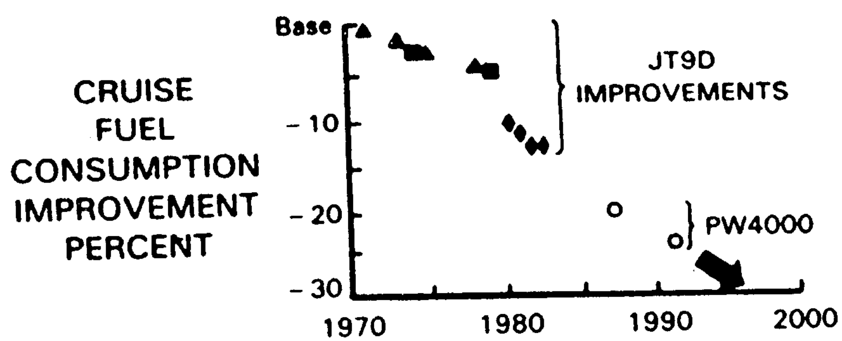


MAJOR GOALS

Military: High Performance

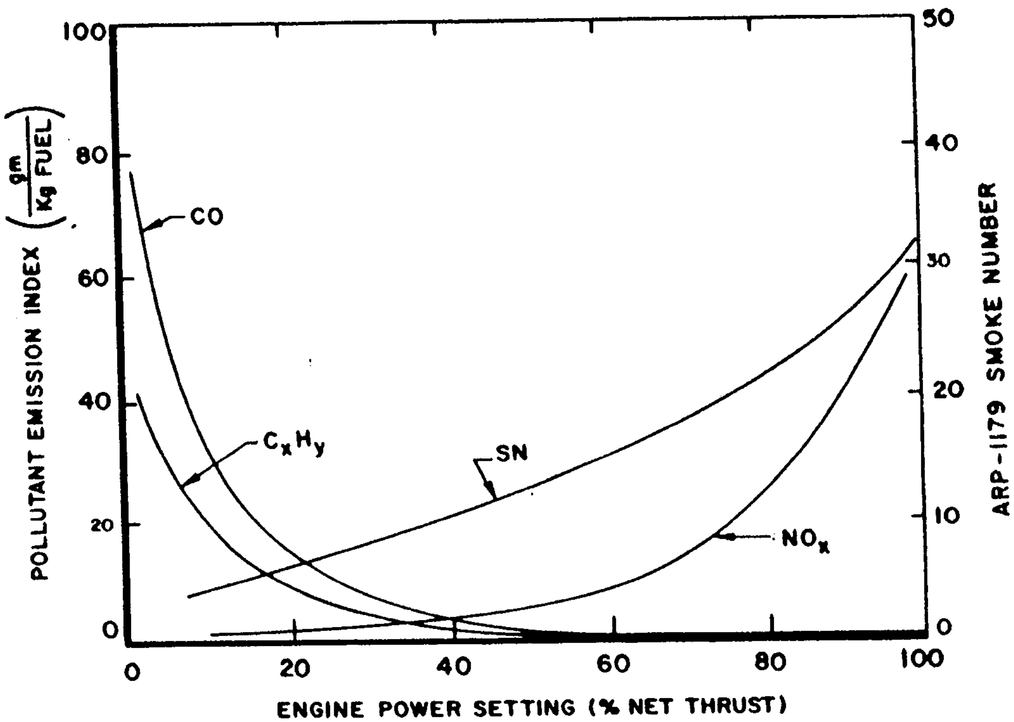
High Exit Temperatures



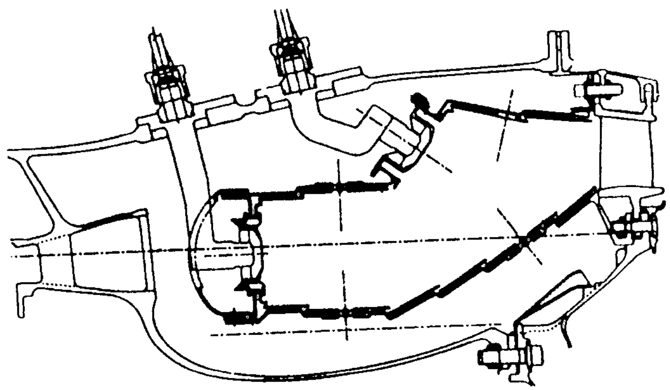


Commercial: Low Pollutants

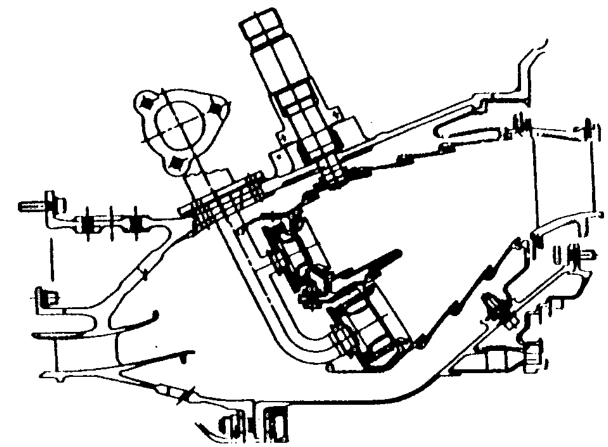
Low Oxides of Nitrogen



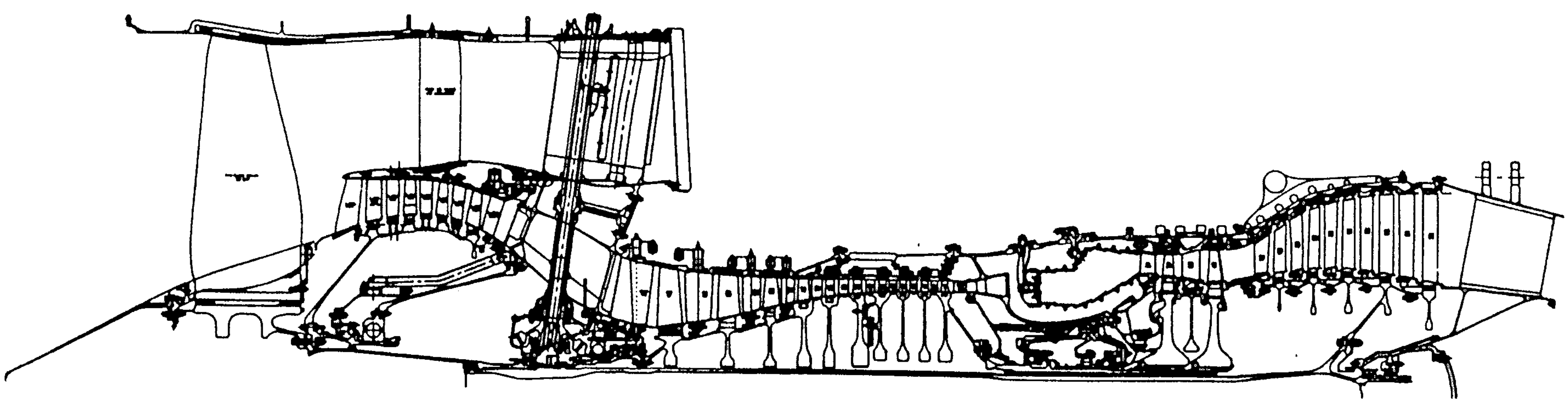
FUTURE GENERATION ENGINES



V2500-5 ASC

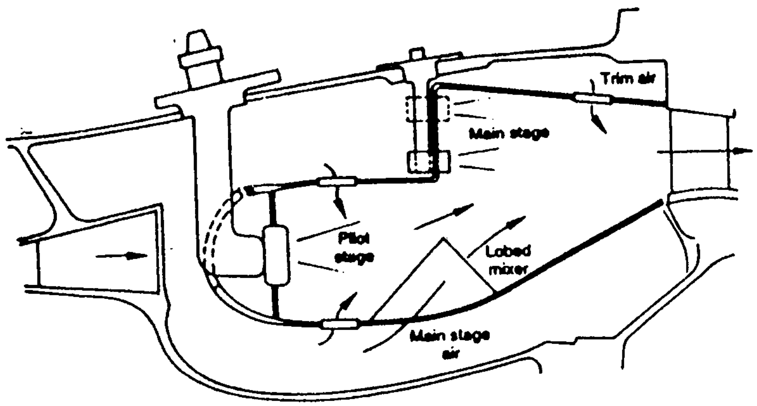


CFM56-5B RSC

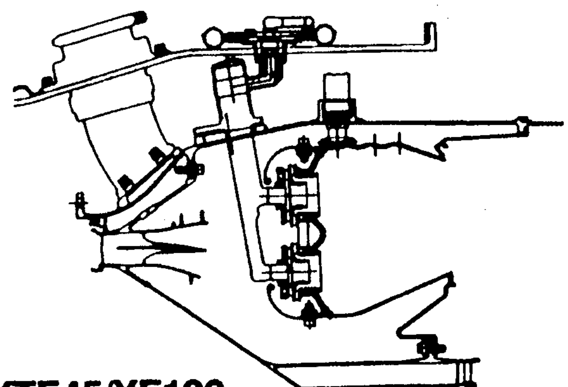


IAE V2500-A5 ENGINE WITH LOW NOx AXIAL STAGED COMBUSTOR (ASC)

6.1 Research Opportunities



Axially Staged Combustor



XTE45/YF120

Radially Staged Combustor

6.1 Research Questions

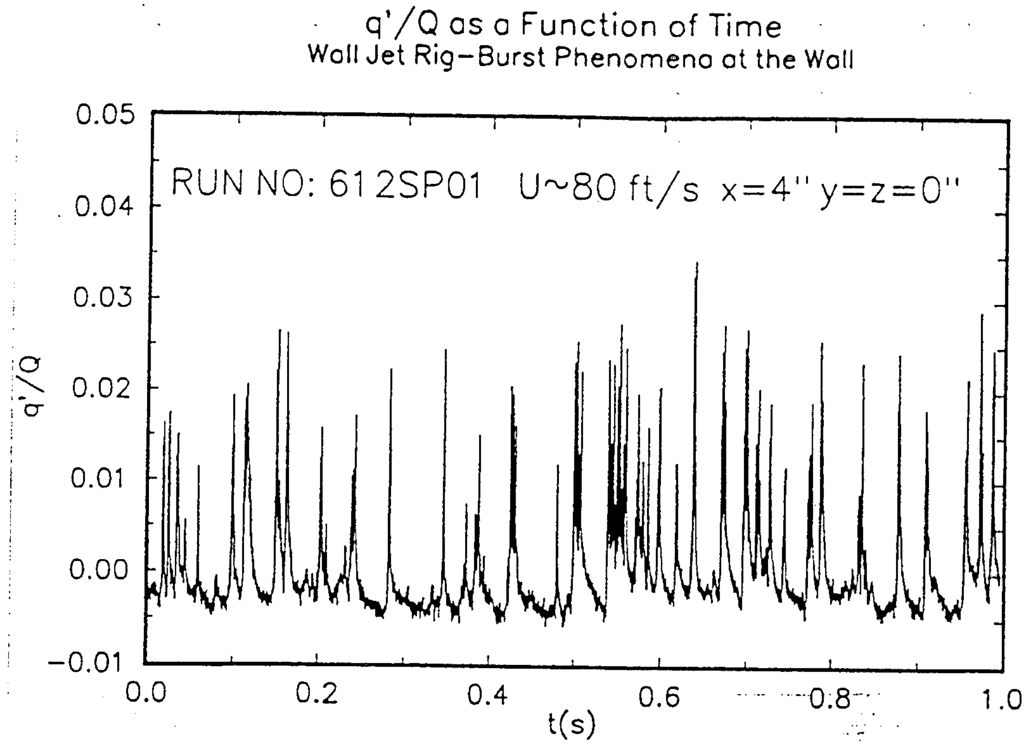
Impact of Unsteady Comb. on Turbine

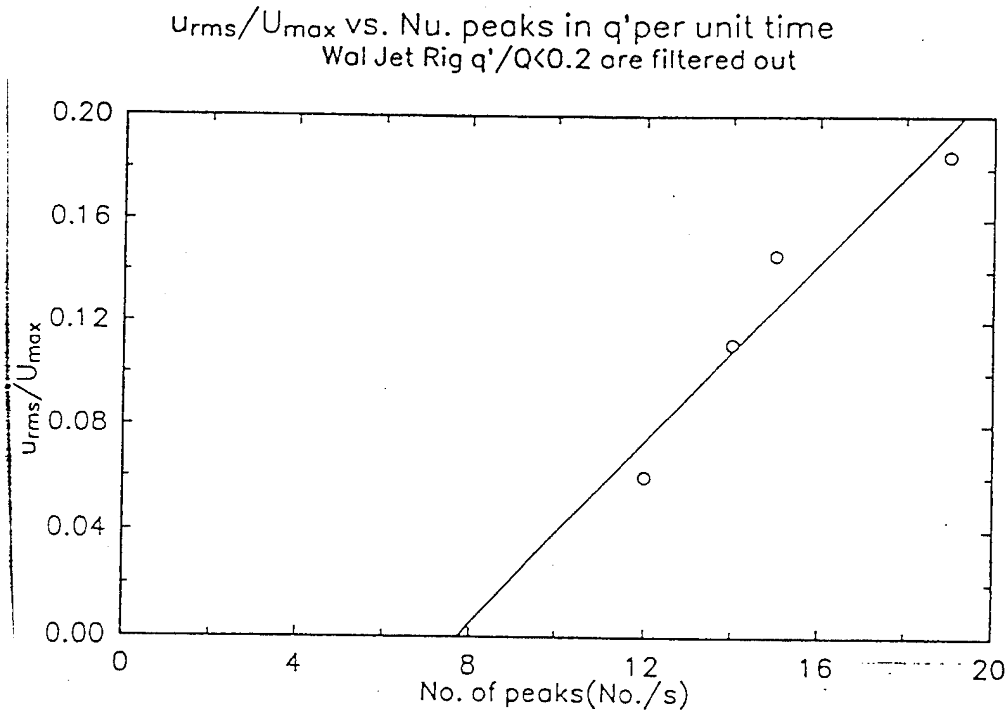
- What is the time history of temperature and velocity exiting advanced staged combustors?
- Do chemical reactions continue to occur in turbine?
- How does unsteady flow affect transport of mass and heat?
- Relationship between large temperature peaks on durability of turbine blades?

EFFECT OF FREE STREAM TURBULENCE ON THE BURST PHENOMENA AT THE WALL IN A WALL JET

SAVAS YAVUZKURT

DEPT. OF MECHANICAL ENGR.
THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK PA 16802


q'/Q as a Function of Time
Wall Jet Rig–Burst Phenomena at the Wall
RUN NO: 612SP01 U~80 ft/s x=4" y=z=0"
q'/Q
t(s)
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
0.0
0.2
0.4
0.6
0.8
1.0


urms/Umax vs. Nu. peaks in q'per unit time
Wal Jet Rig q'/Q<0.2 are filtered out
urms/Umax
No. of peaks(No./s)
0.20
0.16
0.12
0.08
0.04
0.00
0
4
8
12
16
20

- **NUMBER OF EJECTIONS IDENTIFIED BY THE NUMBER OF PEAKS IN THE q' TRACES INCREASE AS THE FREE STREAM TURBULENCE INTENSITY INCREASES**

- **SPACE CORRELATIONS BETWEEN q' AND u' IN THE VERTICAL DIRECTION SHOW THAT THE EFFECTS OF FLUCTUATIONS IN VELOCITY AT LONG DISTANCES FROM THE WALL ARE FELT AT THE WALL**

FREE STREAM TURBULENCE NUMBER

$$\alpha = V_i\overline{u_i'2}/\delta 3U2$$

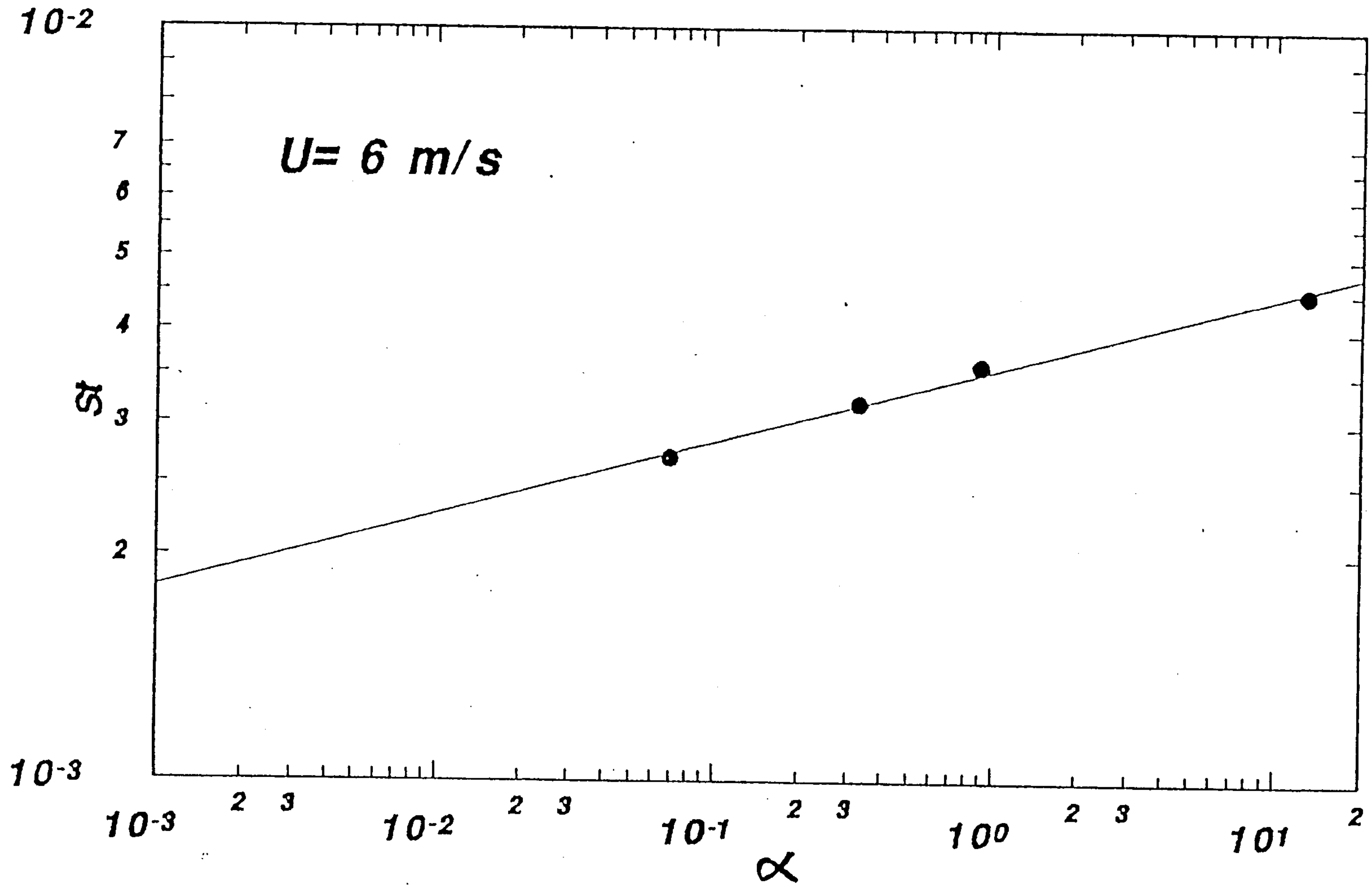
$$V_i\overline{u_i'2} = V_u\overline{u'2} + V_v\overline{v'2} + V_w\overline{w'2}$$

$$V_u = L_{ux} \cdot L_{uy} \cdot L_{uz}$$

IN HIGH FST FLOW REYNOLDS NUMBER HAS NO EFFECT. THE DIFFUSION IS TAKEN CARE OF BY TURBULENCE GENERATED IN THE BOUNDARY LAYER BY THE FREE STREAM TURBULENCE

$$St = C\alpha n$$

STANTON NUMBER AS A FUNCTION OF
FREE STREAM TURBULENCE NUMBER



Combustor / Turbine Interactions

WINCAT

Purdue University

4 October 1993

Forrest E. Ames

Allison Gas Turbine Div GMC

P.O. Box 420, S/C W-16

Indianapolis, Indiana 46206-0420

Office: (317) 230 - 2476

Fax: (317) 230 - 5600

Combustor / Turbine Interactions

"Where should we go and what are useful pathways to gain fundamental knowledge and to transition the findings to advances in technology?"

What are the drivers for turbine technology?

- o Mission capability
- o Efficiency / Weight / Cost
- o Durability / Reliability
- o Emissions
- \+ Higher pressure ratios
- \+ Higher turbine inlet temperatures

What do we need to predict?

- o Gas path heat transfer (film cooling protection)
- o Aerodynamic losses
- o Exit boundary conditions

Combustor / Turbine Interactions

What do we need to know?

- o Inlet conditions:
  - \+ Inlet turbulence characteristics
  - \+ Inlet velocity distribution
  - \+ Inlet temperature distribution

What are the critical interactions?

- o Turbulence / Boundary layer (vane and endwall)
- o Turbulence / Film cooling
- o Film cooling / Heat transfer augmentation
- o Turbulence / Wake
- o Flow field / Turbulence

Combustor / Turbine Interactions

Turbine Design

Empirical Data

Computational Technology

Now

Empirical Data 50%

Computational Technology 50%

10 Years From Now

Empirical Data 25%

Computational Technology 75%

Main Driver is Better Turbulence Modeling

Experimental Data + Computational Research

Combustor / Turbine Interactions

Experimental Data Needs

Inlet Characteristics

Tools

- o Hot wire anemometry -- ambient
- o Laser Diagnostics -- Hot Conditions

Issues

- o Design specific characteristics -- Tu, Lu, T, V
- o Relevance of ambient data -- Tu, Lu

Film cooling with and without free stream turbulence

Tools

- o Hot wire anemometry
- o Mass transfer analogy

  LIF (i.e., acetone), tracer gas measurement
- o Conventional temperature based methods
- o Liquid crystal thermometry

Combustor / Turbine Interactions

Experimental Data Needs

Film cooling with and without free stream turbulence

Issues

- o Influence of turbulence and scale
- o Turbulent mixing
- o Influence of hole geometry and internal flow
- o Heat transfer augmentation
- o Density ratio
- o Aerodynamic losses

Relevant Geometries

- o Flat Plate
- o Accelerating, Wedge Flow, Concave
- o Vane Cascades

Combustor / Turbine Interactions

Experimental Data Needs

Heat transfer and turbulence mechanics

Tools (Varied)

Issues

- o Influence of high turbulence on inlet boundary layers and resulting secondary flows
- o Influence of turbulence and scale on 3-D boundary layers
- o Effect of strain fields and solid surface on turbulence and resulting heat transfer
- o Effect of inlet turbulence on losses and wake development

Relevant Geometries

- o Flat Plate
- o Accelerating, Wedge Flow, Concave, Circular Cylinder
- o Vane Cascade

Combustor / Turbine Interactions

Modeling Efforts

- o Boundary layer calculations
- o 2-D & 3-D Reynolds Averaged Navier Stokes
- o Large eddy simulations
- o Direct numerical simulations

Turbulence Modeling

- o Advanced K - epsilon and K - omega models
- o Reynolds stress models
- o Spectral closure models
- o Subgrid modeling

Combustor / Turbine Interactions

Future Design Efforts

- o Airfoil optimization for heat transfer and passage aerodynamics
- o External cooling / aerodynamic design integration
- o Internal cooling predictive capabilities

E.M. Greitzer, C.S. Tan

MIT Gas Turbine Laboratory

D. Wisler

General Electric Co.

WAVES AND INSTABILITY PHENOMENA IN MULTI-STAGE COMPRESSORS

WAVES AND INSTABILITY PHENOMENA IN MULTI-STAGE COMPRESSORS

E.M. Greitzer, C.S. Tan
MIT Gas Turbine Laboratory

D. Wisler
General Electric Co.

WINCAT
October 4 - October 6, 1993

TECHNICAL OBJECTIVES

- Develop sound physical models of multi-stage compressor response to rotating (unsteady) inlet distortion

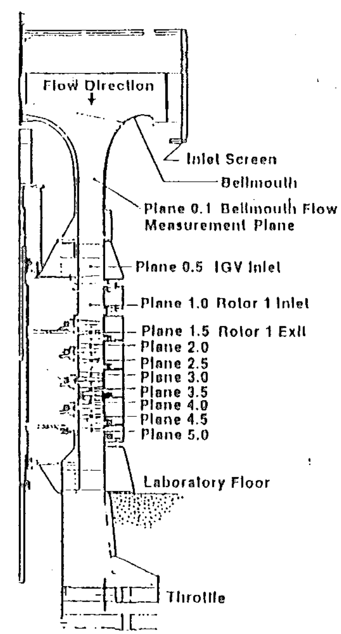
  Two-spool compressors: HPC subject to rotating distortion when fan/LPC in rotating stall

- Assess effect of unsteadiness on stable flow range
- Obtain new diagnostic information for flow model assessment
- Motivate development of new conceptual/ theoretical tools

TECHNICAL APPROACH

- Forced response investigation
  - Rotating screen upstream of low speed multi-stage compressor
- Use present flow model
  - to guide experimental measurement,
  - for physical interpretation of data
- Measurements on research compressor at GE ARL
  - Time-mean data] for advanced compressors
  - Time-resolved data] for advanced compressors
  - Assessment of basic model concepts

CROSS-SECTION OF LOW SPEED GE RESEARCH COMPRESSOR IN 0.7 R/R CONFIGURATION



THEORETICAL MODEL

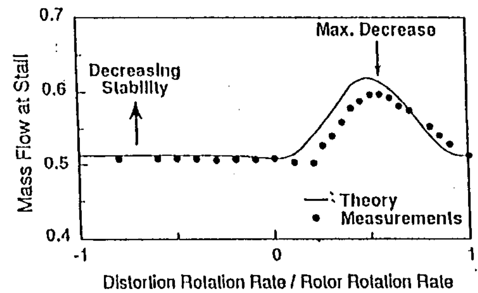
- Based on 2-D unsteady disturbance wave structure
- Flow variation ~ circumference (>> blade pitch)
- Useful for:
  - (1) Stall precursor description
  - (2) Nonlinear evolution into rotating stall
  - (3) Unsteady compressor response to distortion
  - (4) Active and passive control strategies

SOME OVERALL RESULTS

- Sweep of rotation frequencies vs. stall mass flow
- Two types of behavior identified single peaks vs. double peaks
- Two types of resonance => two dynamical system behaviors

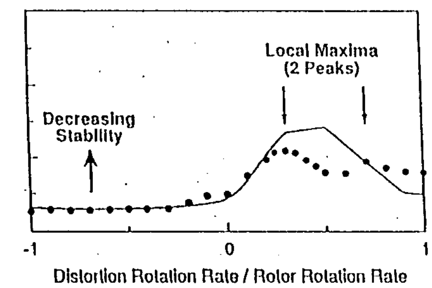
INSTABILITY ONSET SHIFTS DUE TO UNSTEADY DISTORTION
(Qualitative and Quantitative Differences Between Compressors)

COMPRESSOR A –
Long Wavelengths
Dominate Flow Physics



- Theory and experiment agree concerning maximum decrease in stability

COMPRESSOR B –
Time-Resolved Data Shows That Short
Wavelengths are Critical in Stall Onset



- Two local maxima; one associated with short wavelength instability theory

NEW FINDINGS

- Two groups of compressors in terms of response to rotating distortions
  - (1) Single Peak Stall Margin Decrement:
    $\Omega_{distortion} \sim 0.3 \quad \Omega_{compressor}$
  - (2) Double Peak Stall Margin Decrement:
    $\Omega_{distortion} \sim 0.3$ and $0.7\ \Omega_{compressor}$
- Multi-stage compressor can have more than one characteristic resonance
- Prediction of behavior in (2) beyond current predictive tools

ROUTES TO STALL IN MULTISTAGE COMPRESSOR

(1) Long wavelength 2-D modal type of stall precursor

$\Omega_s \sim 0.3 - 0.5\ \Omega_{compressor}$

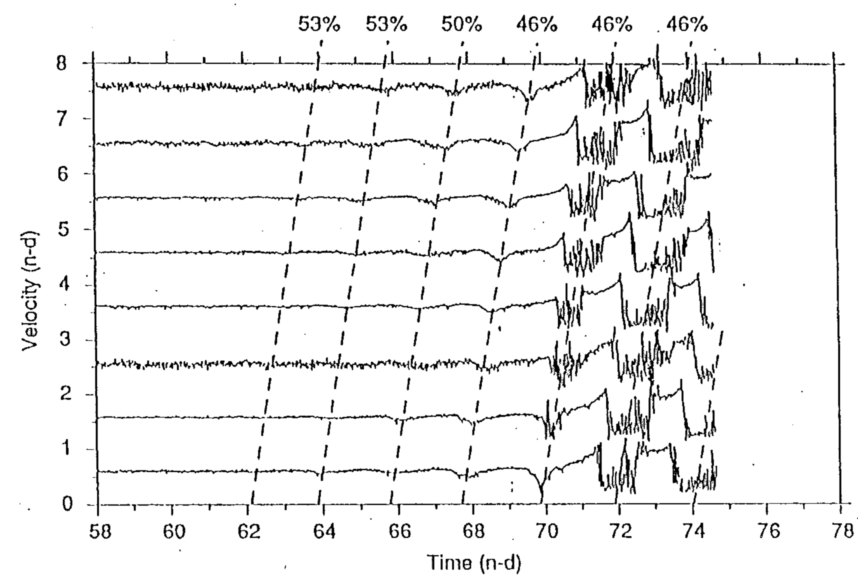
(2) Short wavelength 3-D type of stall precursor (PIP)

$\Omega_s \sim 0.7 - 0.8\ \Omega_{compressor}$

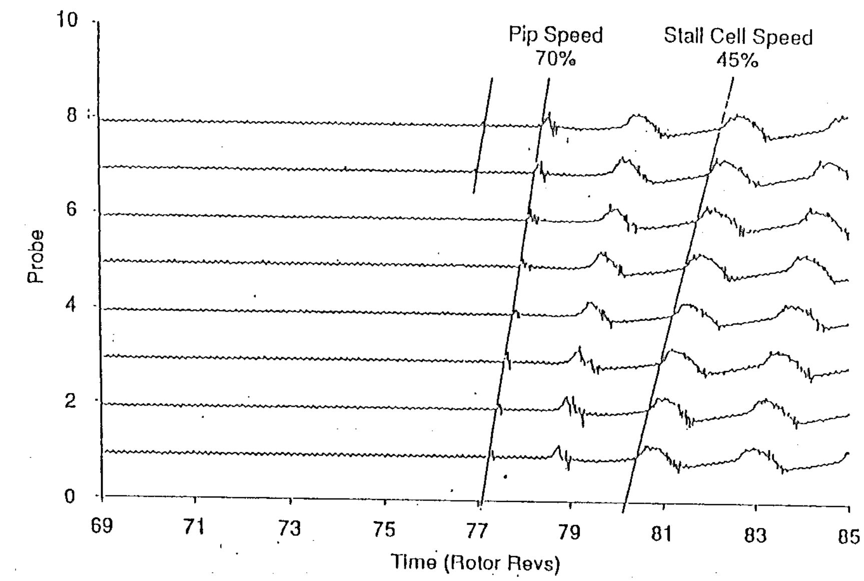
Recent finding (Day 1992)

Two resonant peaks are no coincidence!

LONG WAVELENGTH TYPE OF STALL PRECURSOR (Modal)



SHORT WAVELENGTH TYPE OF STALL PRECURSOR ("Pip" After Day)



CONNECTION BETWEEN NATURAL AND FORCED RESPONSE EXPERIMENT

- View Compressor as a dynamical system
- Two routes to rotating stall onset
- "Steady state" behavior in forced response experiment:
  - directly reflects detailed unsteady flow effects
  - nature of stall precursors impacts distortion sensitivity

SUMMARY AND CONCLUSIONS

- Forced response experiments a new diagnostic tool
- Characteristic resonances & response to distortion linked to Nature of stall precursor disturbances
- Present study points to:
  (i) where current 2-D flow model is adequate
  (ii) need of new 3-D flow model for prediction
  (iii) establishment of causal link between flow instabilities & compressor characteristics
- Reinforces view of compressor flow instabilities as wave phenomena

F.K. Moore

Cornell University

UNSTEADY FLOW IN TURBOMACHINES

Notes for invited talk at WINCAT , Purdue University, 10/4/93

UNSTEADY FLOW IN TURBOMACHINES**

F.K. Moore**

INTRODUCTION

- o Inherently unsteady, despite regularities intended in design. Unsteadiness is in the details, because design is steady.

- o Performance and instability
  - > Nonlinear connection of the two--e.g., by "inlet distortion".
  - > Will emphasize instabilities
  - > Will emphasize importance of the engine inlet (which connects to the compressor).

Outline of Talk:

1. Comments about unsteady viscous flows.
2. System oscillations, inlet distortion.
3. Opportunities for passive mode suppression.
4. Research program suggestions.

* Relevant research largely supported by NASA-Lewis

** Cornell University

1. UNSTEADY VISCOUS FLOWS

o Waves arise from nonviscous features, such as

> Additional apparent mass
> Acoustics
> Vortex shedding

because machine is intended to be inviscid, but has many relevant scales.

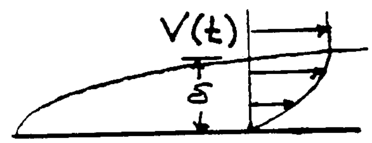
o Waves damped or amplified by viscous or chemical-kinetic effects.

Note: In a dissociating gas, chemistry disperses sound waves: If "frozen" and "equilibrium" sound speeds are in the ratio $1+\varepsilon$, and reaction time is τ, then the damping factor (mimicing viscosity) is $\sim \exp[-\varepsilon\tau\omega^2 t]$.

o Boundary layers:

Diffusion time: $t_d = \delta^2/\nu$

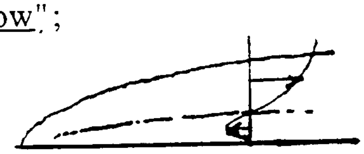
Wave period: $t_w = 1/\omega$



If $\dfrac{t_d}{t_w} = \boxed{\dfrac{\delta^2\omega}{\nu}} << 1$, then the boundary layer is "quasi-steady".

(The wake behind an unstalled airfoil is likely thin, so it is q.s., and the Kutta condition no doubt applies.)

If $\dfrac{\delta^2\omega}{\nu} >> 1$, then one has a "Stokes flow"; the action is at the base of the b.l., and C_f leads $V(t)$ in phase.

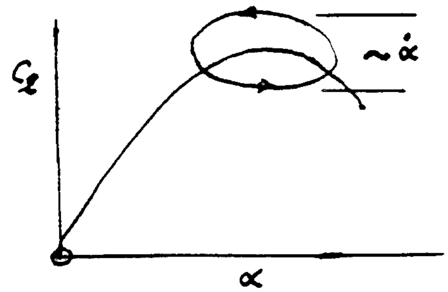


o Viscous effects in high-Re machines usually at least nearly q.s.

> Ex.: Airfoil at $C_{\ell_{max}}$ and α fluctuates.

- In principle, this gives unsteady b.l. problem, with lift hysteresis.

- Result dominated by the q.s. movement of the upper separation point (P) as α changes.



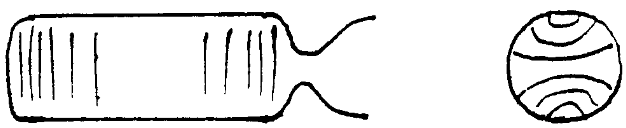
> When we use the "axisymmetric characteristic" to evaluate surge or rotating stall stability, we are invoking the nearly-q.s. assumption for the viscous stall process. That is, we are thinking about the following expansion (e.g. for the airfoil problem above, where we imagine time scaled by the time for flow passage over the chord):

$$C_l = \underbrace{\begin{array}{c} C_{l_0} \\ \alpha \\ \alpha^2 \\ \vdots \\ fn_0(\alpha) \end{array}}_{\text{q.s.}} + \underbrace{\begin{array}{c} \dot{\alpha} \\ \alpha\dot{\alpha} \\ \vdots \\ \dot{\alpha}\, fn_1(\alpha) \end{array}}_{\text{"nearly q.s."}} + \begin{array}{c} \ddot{\alpha} \\ \dot{\alpha}^2, \alpha\ddot{\alpha} \\ \vdots \end{array} + \begin{array}{c} \vdots \end{array}$$

If we keep the first circled group, then we are saying q.s. If we add the second circled group (with single dots) we are making a first correction; the hysteresis in the sketch represents this group of terms. A further correction would involve terms with two dots, and so forth. This framework helps to discipline calculations and experiments. Note how important for experiments to know q.s. approximation is OK!

2. SYSTEM OSCILLATIONS

o Acoustic: Recall "screech" of rocket engines.

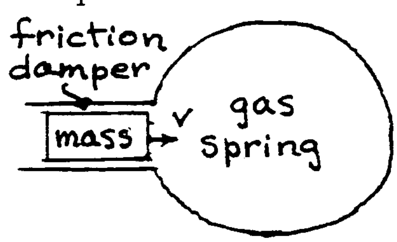


> "Organ-pipe" or "sloshing" (maybe "spinning") modes.
> Chemistry and viscosity amplify and damp oscillation.
> Wave interactions with nozzle important for organ-pipe.

Note that large scale and distant boundaries allow many modes. Openness for the sake of throughflow, symmetries, and evenness of spacings (cultural imperatives for the engineer!) all encourage mode formation.

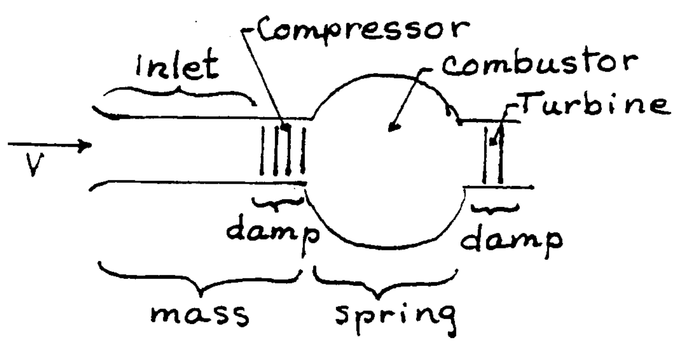
• System oscillations are typically governed by this equation:

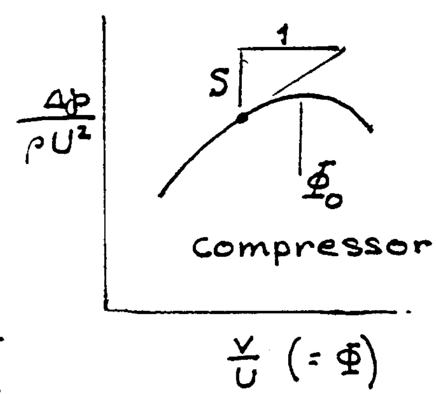
$$\boxed{\underbrace{m\dot{v}}_{\text{mass}} + \underbrace{cv}_{\text{damper}} + \underbrace{k\int v\,dt}_{\text{spring}} = 0}$$



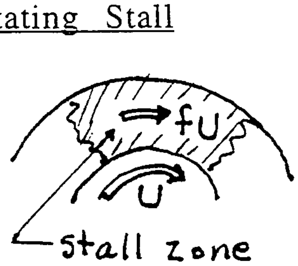
The "Helmholtz oscillator" is an example: (in which fluid comprising the "piston" is assumed to move quasi-steadily as regards sound propagation):

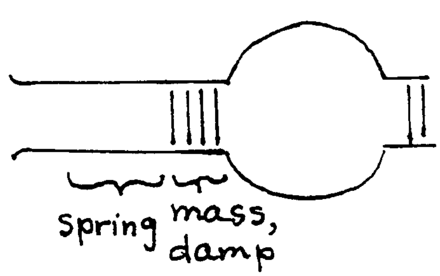
o Surge



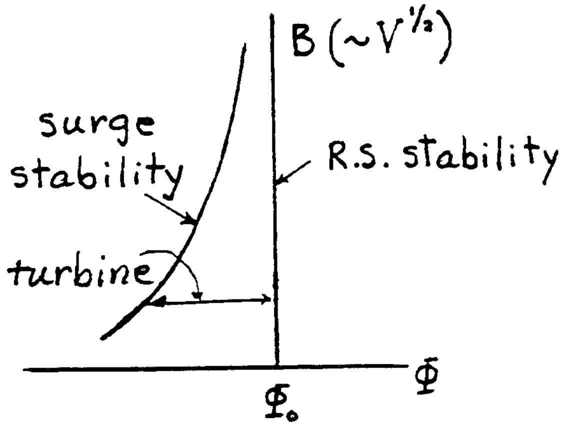


o Rotating Stall

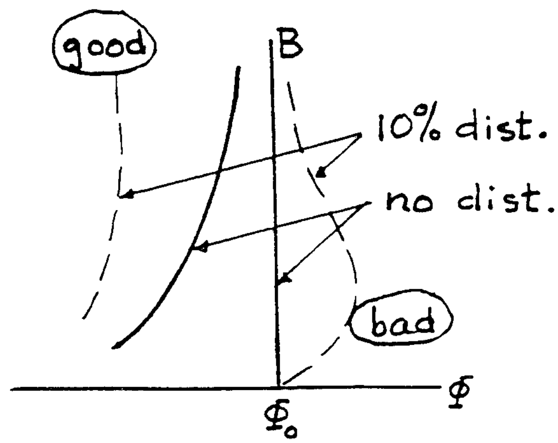




o Surge and R.S. are both system oscillations quite like Helmholtz.
> For R.S., a characteristic slope S > 0 amplifies.
> For Surge, S > 0 tends to amplify, but "leaky plenum" (turbine) tends to damp.
> Inlet is to R.S. as the Combustor is to Surge.
> One should study unsteady behavior of components as they function in a system.

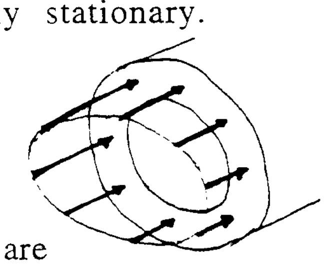


(F. McCaughan, CU PhD '88)



(W. West, CU PhD '93)

o Inlet Distortion--a circumferential mode, but usually stationary.
> Affects performance.
> Bad for r.s. stability, but blade lag reduces "badness" (W. West '93).
> Apparently "good" for surge!
> Varieties of distortion (circular asymmetries) are hardly scratched (Modes, effects of inlet length and shape, whether of potential or shear type, unsteady, . . .)



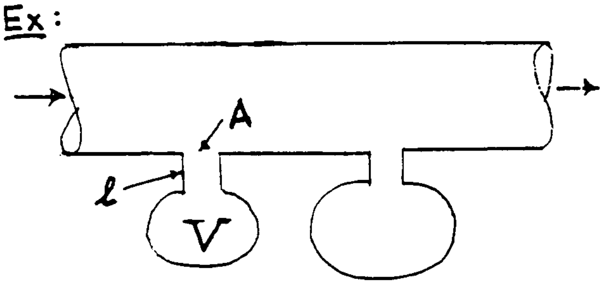
3. PASSIVE MODE SUPPRESSION

$$\boxed{m\dot{V} + cV + k\int V\,dt = 0}$$ is an overall pressure balance.

o Need a $\Delta p \sim V$ relation of right phase, to

> modify inertia or spring elements suitably, or
>
> encourage viscous damping:
>
> Resonance--> high velocities--> frictional damping.

Ex:



$$\boxed{\omega_H = a\sqrt{\frac{A}{\ell V}}}$$

(Helmholtz Osc.)

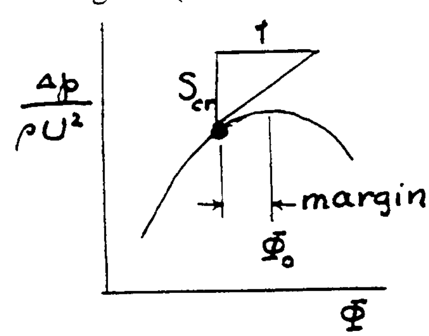
> Should affect large mass where it matters--Inlet for R.S., Combustor for Surge.
>
> Don't worry too soon about practicality!
>
> Passive if possible!

o <u>For Surge</u>: Give combustor a compliant wall ($V \sim \Delta p$)?--remember turbine!

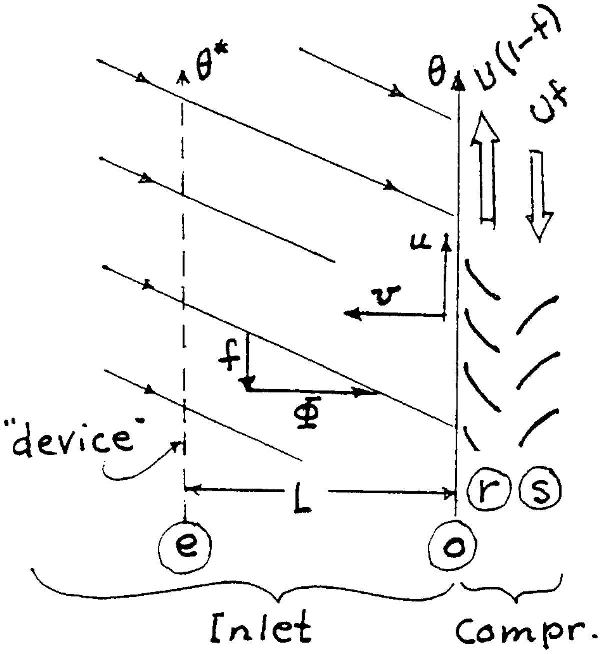
> Geometry of combustor?
>
> Chemistry?
>
> Secondary resonant oscillators?
>
> Also remember favorable effect predicted for inlet distortion!

o <u>For Rotating Stall</u>: Work on <u>inlet</u> to increase "margin" (make the critical value of S_{cr} as positive as possible.)

> Consider some "devices" at some axial location (L) in otherwise straight inlet, find the critical S. Potential flow in inlet, except across device.



> Those interested in r.s. theory might look at "unwrapped" inlet, in frame of r.s. pattern maybe rotating at speed $f \cdot U$:



$$\lambda \frac{dv_0}{d\theta} - S v_0 - f u_0 = \mathcal{J}_e(\theta^*)$$
where device gives
$$\mathcal{J}_e = \frac{p_e - \bar{p}_e}{\rho U^2} + \Phi v_e - f u_e$$

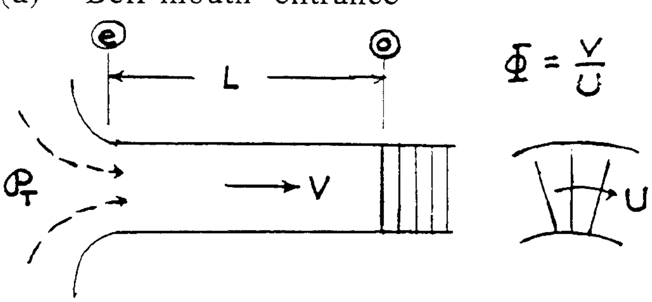
> If no p_T change at (e), $\mathcal{J}_e = 0$, and usual r.s. result applies.

> S_{cr} and λ are eigenvalues.

> Why is inlet a "spring"? Disturbance v induces u, which gives a Δp which is 90 degr. out of phase with v, as a spring does.

> **Problem: How to change u_0, v_0 relation beneficially.**
<u>Here are some inlet devices affecting r.s. margin:</u>

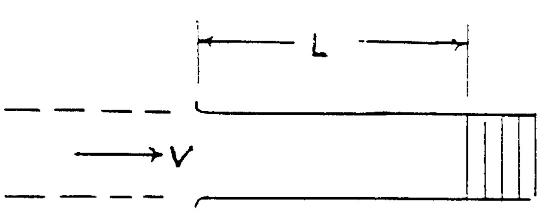
(a) Bell-mouth entrance



$\Phi = \frac{V}{U}$

$S_{cr} = 0$ (usual)

(b) "Flight" entrance

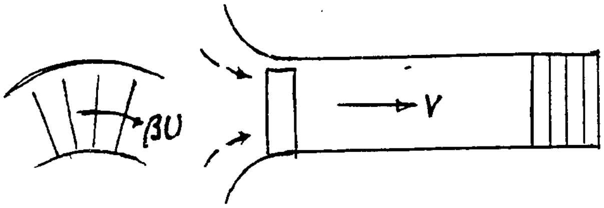


$S_{cr} = 0 \quad (L = \infty)$

$= -\Phi \quad (L = 0)$

(bad)

(c) Free rotor, or unloaded fan; speed βU, bell type entrance

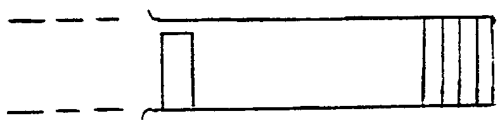


$$S_{cr_0} = \frac{\beta^2}{\Phi} \quad (\text{for } L \to 0)$$

(good)

> Good effect of "free rotor" first suggested by D. Gysling (MIT PhD 93)

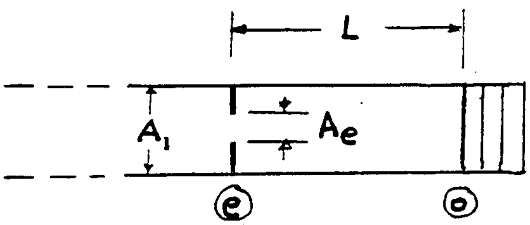
(d) Free rotor, flight type entrance



$$S_{cr_0} = (\beta - f)\frac{\Phi}{f} + \frac{\beta^2}{\Phi}$$

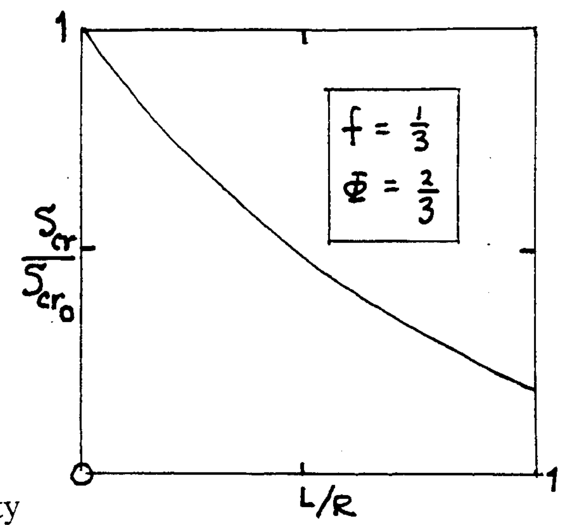
(good, if $\beta > f$)

(e) Radial slot, infinite inlet

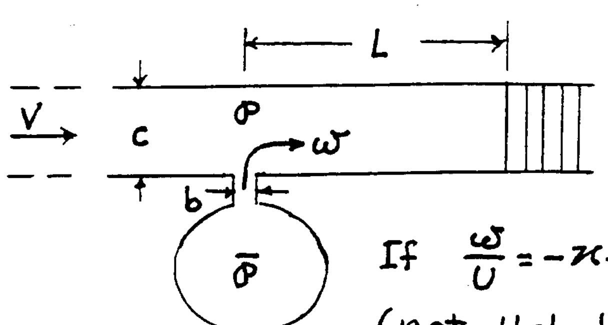


$$S_{cr_0} = \left(\frac{A_1}{A_e} - 1\right)^2 \Phi$$

(good)



(f) Wall slot, large cavity



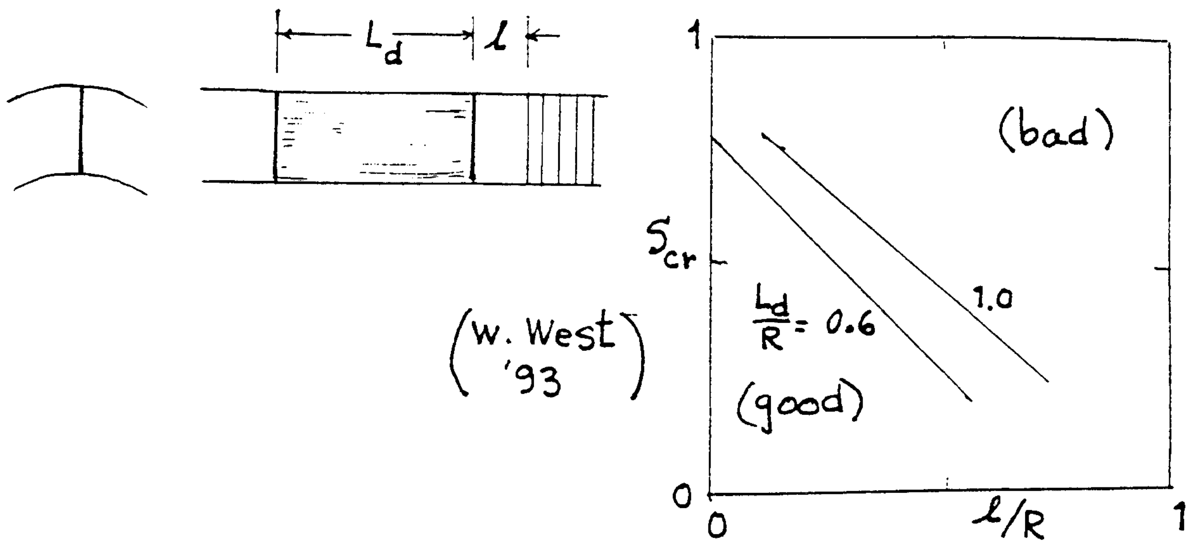
$$S_{cr_0} = \frac{b}{c}\varkappa(\Phi^2 + f^2)$$

(good)

If $\frac{\omega}{U} = -\varkappa \frac{\mathcal{P} - \bar{\mathcal{P}}}{\rho U^2}$

(not Helmholtz ; $\bar{\mathcal{P}}$ constant)

(g) Axial divider, or "splitter"*



> All of above "work on" connection between axial and transverse velocity disturbances at compressor face, due to waves.

> Only the "splitter" (g) could be said to work on all the mass in the inlet, and the predicted effect on margin is therefore the greatest.

> Transverse devices (c)-(f) have greatest effect for L = 0; must be within 1 wheel radius of compressor face.

> Effects of all devices depend on blade lag and number of stages.

> Acoustic modes of inlet might resonate with r.s. (frequencies are comparable.)

> What about asymmetry of inlet geometry?

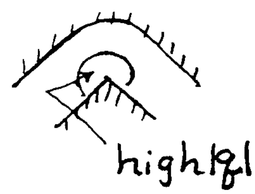
* This concept is the subject of a patent application by the Cornell Research Foundation.

4. RESEARCH PROGRAM SUGGESTIONS

- o Study unsteady flows of all components as they interact in system modes (especially inlet, including fan, and combustor). Include--
  - > "Real" inlet distortion
  - > Acoustic and shock waves
  - > Friction and heat transfer
  - > Chemical kinetics (wall quenching, burn-in-rotor?)
  - > Conform to consistent (nearly-q.s.) expansion.

- o Include acoustics in CFD, so that generation and interaction of all sound fields are predicted.
  - > Noise per se
  - > Generalized Helmholtz oscillator.

    Absorb wave energy at any surface where velocity is high. Study perforated walls.



- o Do experiments with inlet modifications and devices (maybe also the combustor).
  - > Easy to do! (Easier than changing compressor cores, anyway)
  - > Surprises? Ideas won't come from CFD, and theory is too hard.

- o Major facilities (AF, NASA) must be flexible and responsive, because experiments on system modes, and CFD with acoustics, need big-time capabilities. Institutionally, how?

Robert E. Kielb

GE Aircraft Engines
Cincinnati, Ohio

AEROMECHANICS

Aeromechanics Research Topics

Flow Defects
- Wakes
- Potential Disturbance
- Combined Wake/Potential
- Inlet Distortion
- Shock
- Passage Vortices

Unsteady Blade Loads
- Aerodynamic Forcing Function
- Aerodynamic Damping

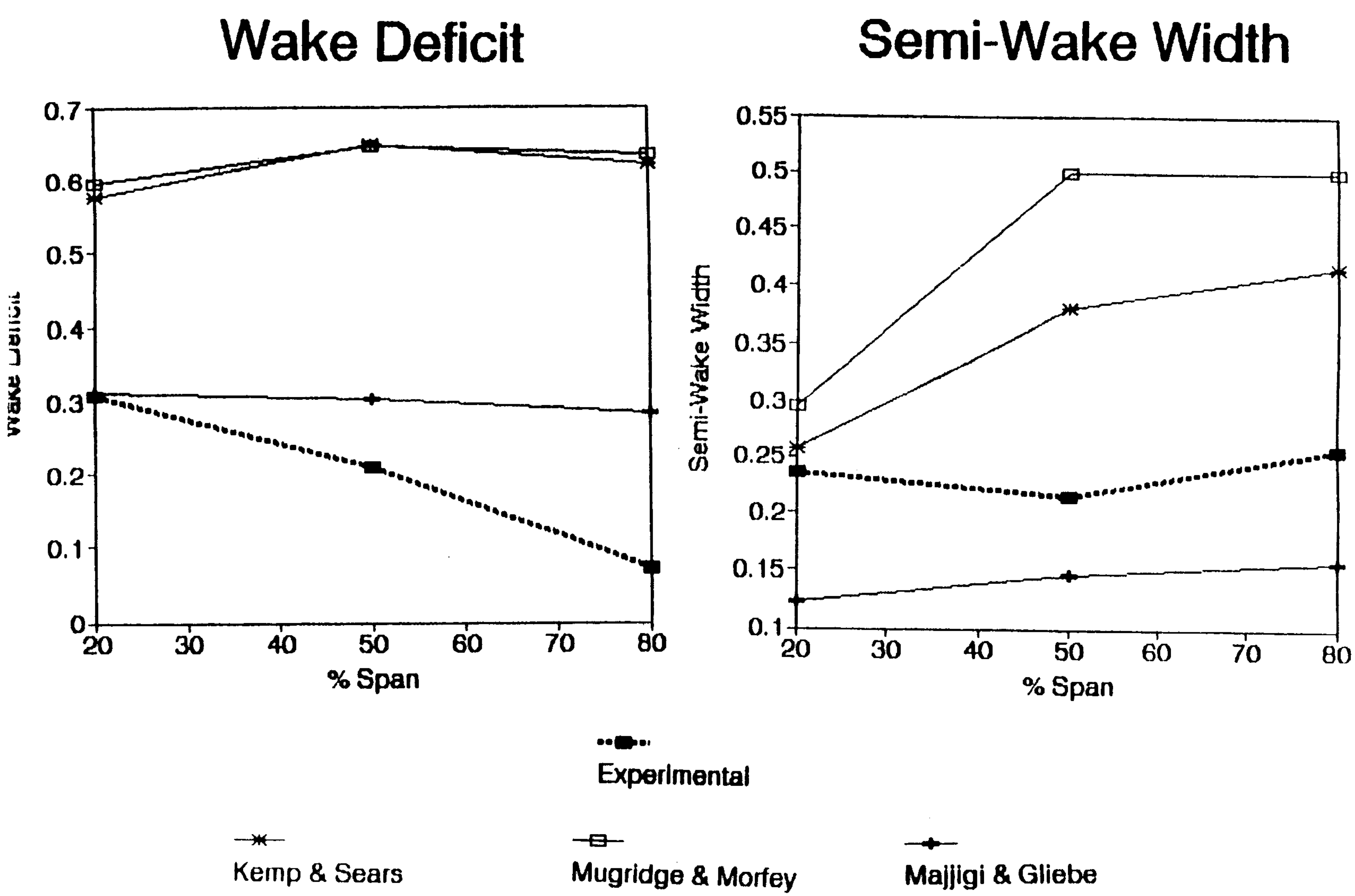
Blade Response
- Tuned
- Mistuned
- Damping

Aeromechanical Concerns

- **Forced Response**
  - Integral Order
    - Aerodynamic: Potential & Wake
    - Mechanical
  - Non-Integral Order
    - Separated Flow Vibration
    - Rotating Stall
  - Transient
    - Surge

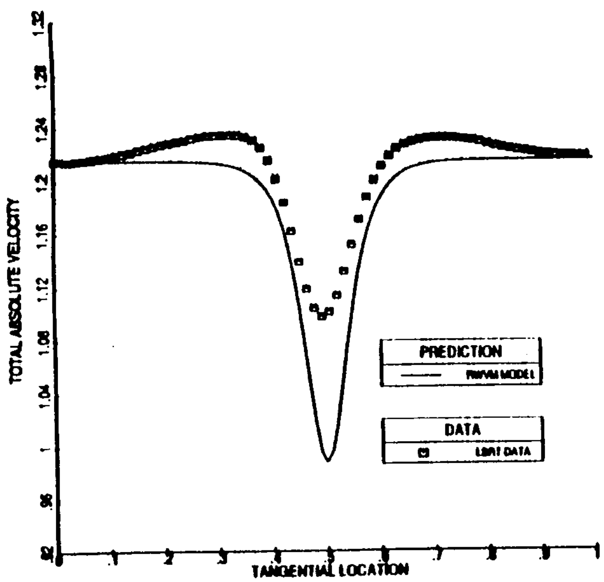
- **Instability**
  - Stall Flutter
  - Choke Flutter
  - Supersonic Unstalled Flutter
  - Coupled Mode Flutter (Low Mass Ratio)

Comparison of Wake Empirical Models

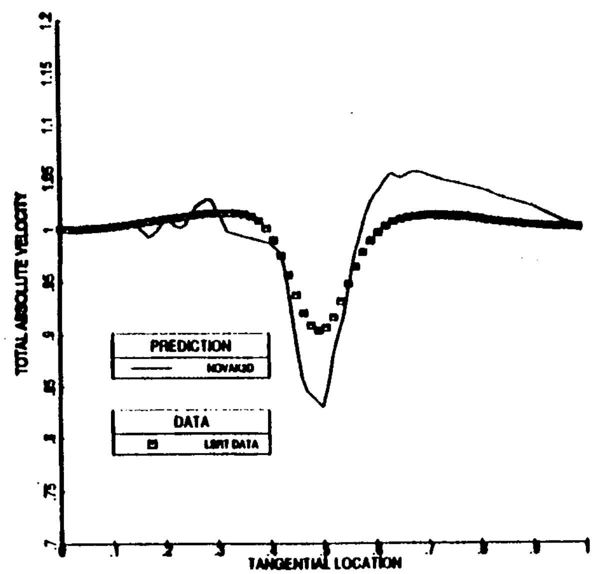


COMPARISON OF WAKE CFD MODELS

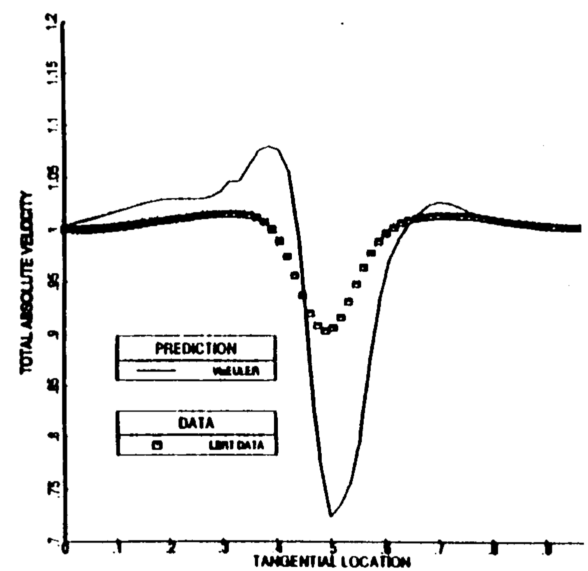
LP Turbine Wakes



RWVM



NOVAK



Viscous Euler

Measurements show that analyses overpredict wake strength

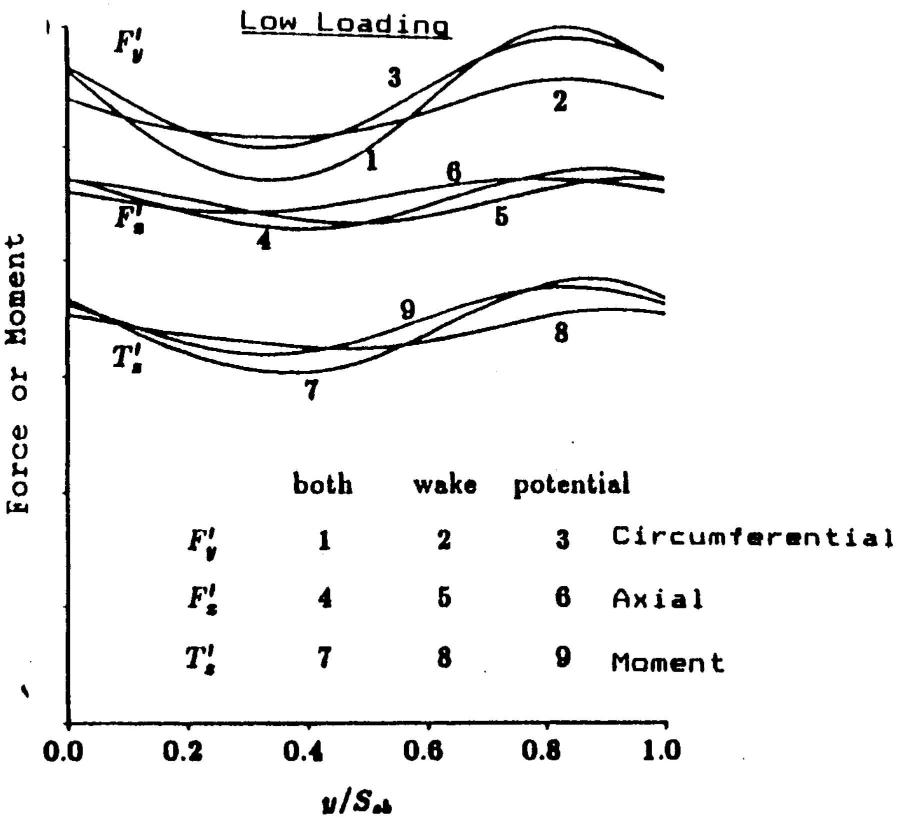
WAKES

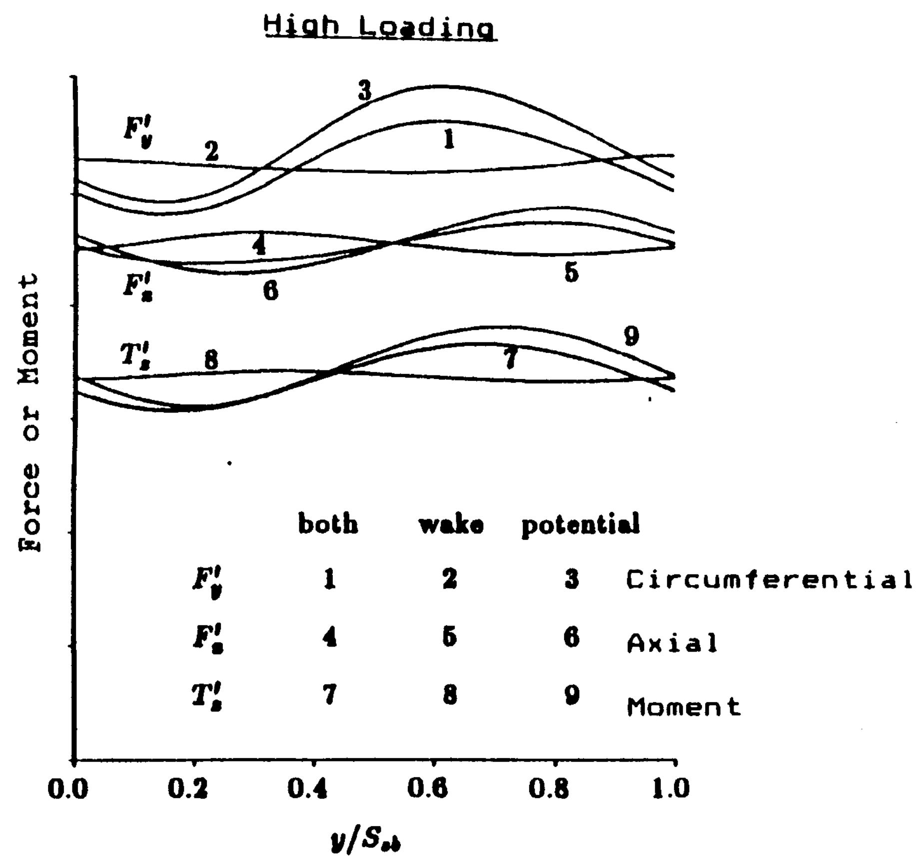
- STATE OF TECHNOLOGY
  - PREDICTION CAPABILITY POOR
- RESEARCH NEEDS
  - LARGER EMPIRICAL DATA BASE
    - NEAR WAKE REGION
    - TURBINE BLADES
  - IMPROVED TURBULENCE MODELS

POTENTIAL DISTURBANCES

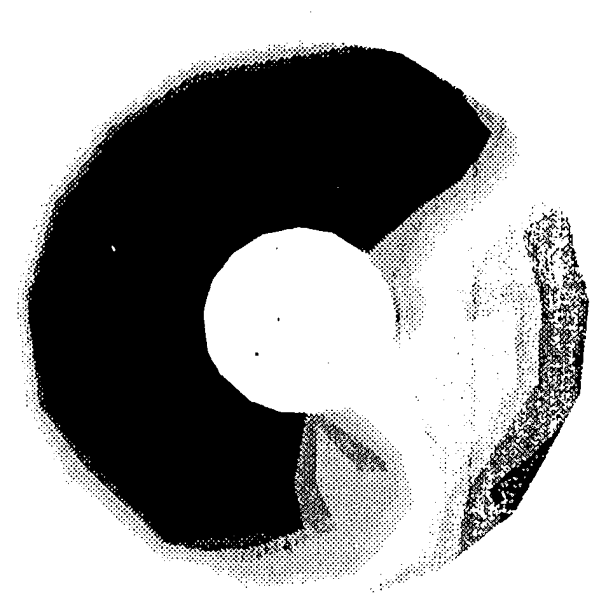
- STATE OF TECHNOLOGY
  - SUBSONIC POTENTIAL EASILY MODELED
  - MULTISTAGE EFFECTS UNKNOWN
- RESEARCH NEEDS
  - MULTISTAGE MODELS

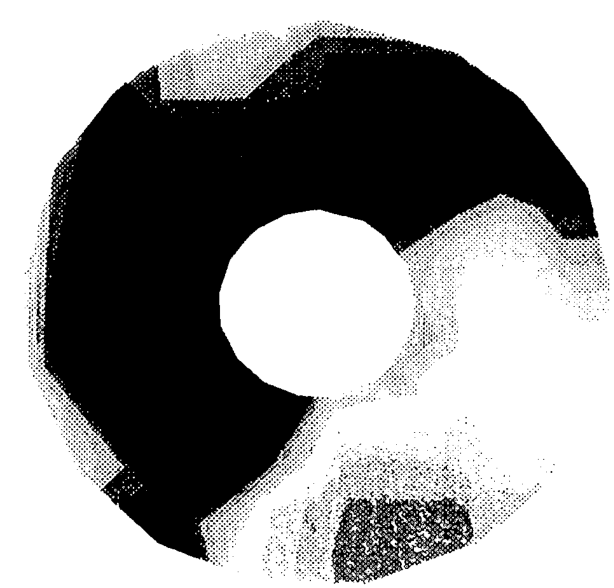
WAKE POTENTIAL INTERACTION





INLET DISTORTION DATA





INLET DISTORTION

STATE OF TECHNOLOGY
- MEASUREMENTS ARE EXPENSIVE
- CFD GOOD FOR ATTACHED FLOWS

RESEARCH NEEDS
- IMPROVED MEASUREMENT TECHNIQUES
- SEPARATED FLOW MODELS

SHOCKS

STATE OF TECHNOLOGY - PREDICTION CAPABILITY POOR

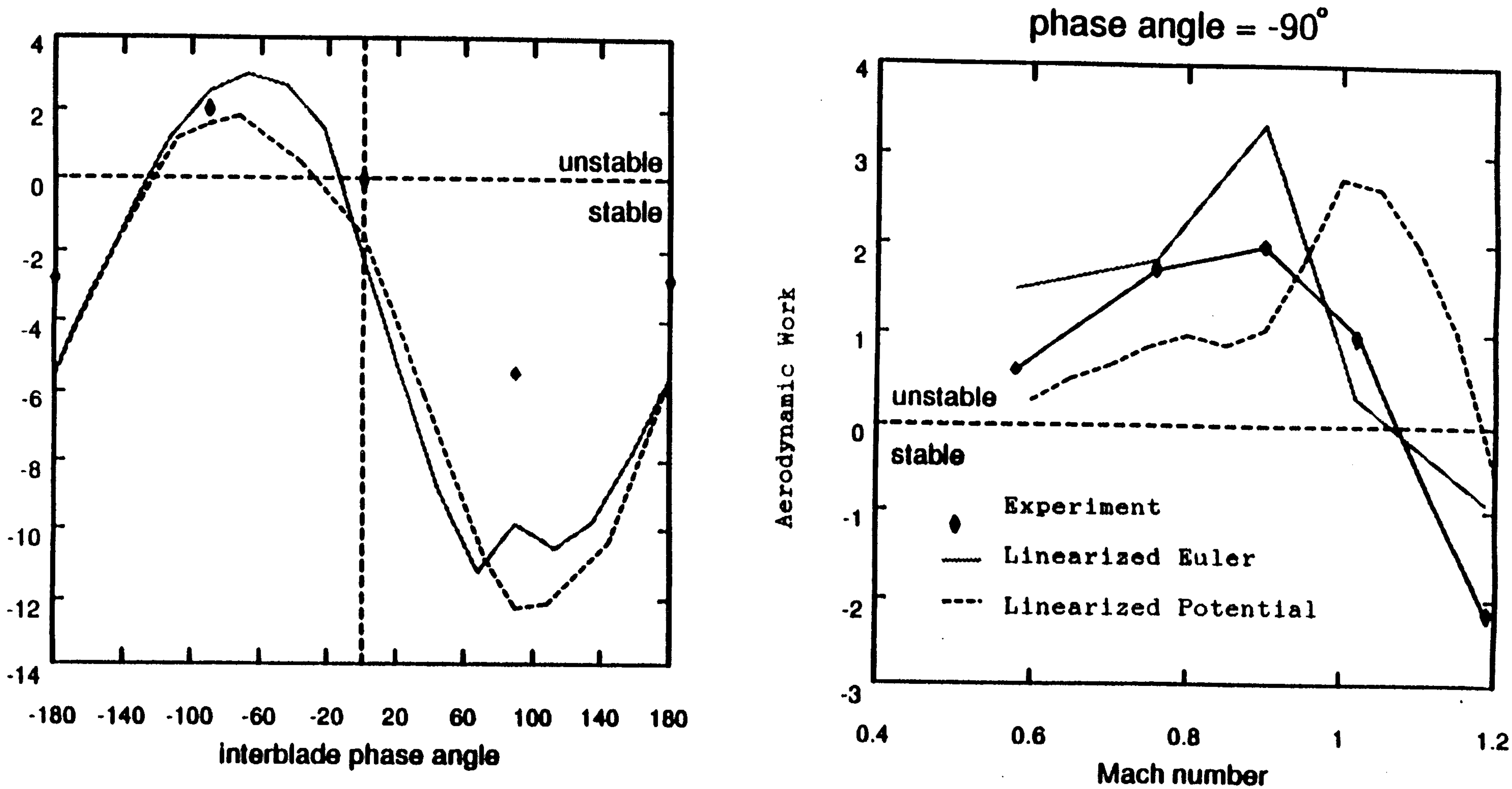
RESEARCH NEEDS - SHOCK/BOUNDARY LAYER INTERACTION MODELS

PASSAGE VORTICES

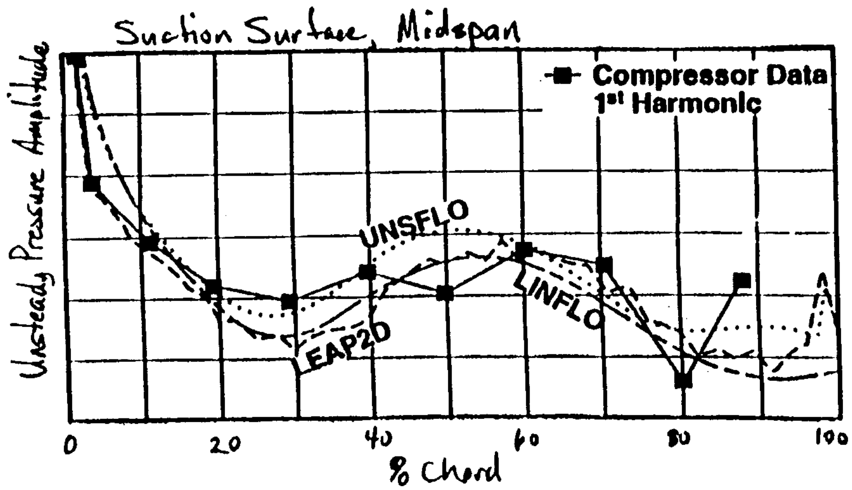
STATE OF TECHNOLOGY - EXISTING MODELS UNVERIFIED

RESEARCH NEEDS - MODEL DEVELOPMENT AND VERIFICATION

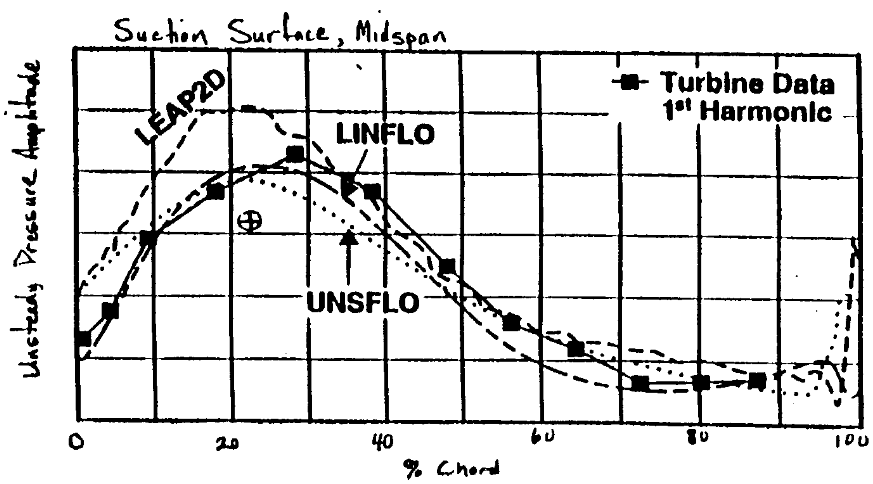
Unsteady Aero Comparisons - Blade Motion



UNSTEADY LIFT DUE TO WAKES



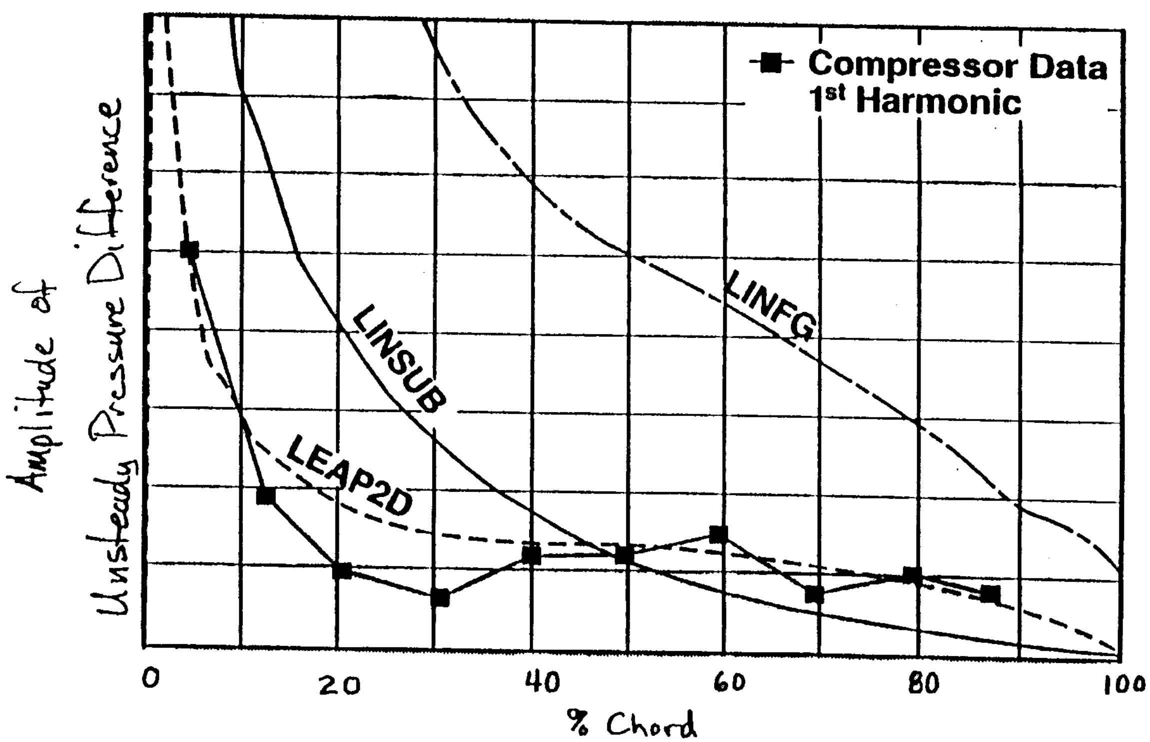
Compressor



LP Turbine

UNSTEADY LIFT DUE TO INLET DISTORTION

Unsteady lift due to inlet distortions



UNSTEADY BLADE LOADS

STATE OF TECHNOLOGY
- LINEARIZED POTENTIAL & EULER CODES
- DISTORTED GUST MODELS RECENTLY DEVELOPED
- LINEARIZED NAVIER STOKES IN DEVELOPMENT

RESEARCH NEEDS
- SEPARATED FLOW MODELS
- ADDITIONAL MODEL VERIFICATION
  - 2D & 3D LINEARIZED EULER

SUMMARY

CURRENT PREDICTION CAPABILITY IS FAIR

MAJOR IMPROVEMENTS NEEDED IN:

- WAKES
- MULTISTAGE EXCITATION MECHANISMS
- UNSTEADY LOADS - SEPARATED FLOW
- SEPARATED INLETS
- SHOCK/BOUNDARY LAYER INTERACTION
- PASSAGE VORTICES
- ACOUSTIC EXCITATION
- DESIGNING LOW RESPONSE BLADES

Sanford Fleeter

School of Mechanical Engineering
Purdue University

AERO - MECHANICS

AERO - MECHANICS

Sanford Fleeter

School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907

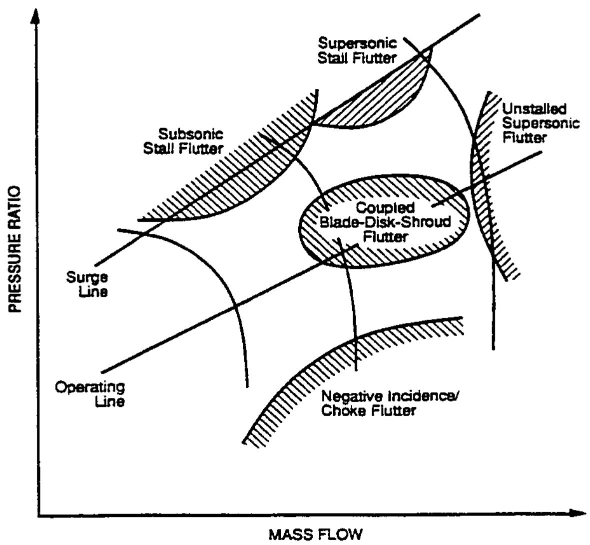
SUMMARY

Aero-mechanics, i.e., forced response and flutter, is a significant concern in the design and development of current and future fans, compressors & turbines. For example, every new gas turbine has had at least one blade row or stage with aero-mechanics problems, with each engine company having at least one such problem and often more. Engine and component vibration have historically been a major source of development expense, with much of the current cost of developing a gas turbine engine a the result of unplanned effort resulting from design deficiencies which are discovered only during initial testing. To meet defense related aircraft propulsion needs into the next century, the Department of Defense is pursuing aggressive improvements in turbine engine propulsion capability. As outlined in the Integrated High Performance Turbine Engine Technology (IHPTET) Initiative, the goal is a doubling of propulsion engine capability by the Year 2003. Engine requirements needed to achieve the IHPTET goals include decreased weight and frontal area, increased thrust/power ratio and improved cycle efficiency. Also, with the current economic and political climate, future engine thrusts will be directed at advanced high performance engines with minimal direct operating costs. Thus, technology which will result in increased efficiency, lighter weight engines with improved reliability will be featured. Unfortunately, both the IHPTET and future engine requirements result in design features which add significant aero-mechanics risk which may jeopardize plans to meet overall goals, i.e., traditional methods of designing turbomachinery blading free from destructive levels of resonant response will not meet the challenges presented by the next generation of engines. Thus, blade aero-mechanics is a critical problem that must be addressed and solved to meet the planned objectives of increasing the performance of advanced fighter engines.

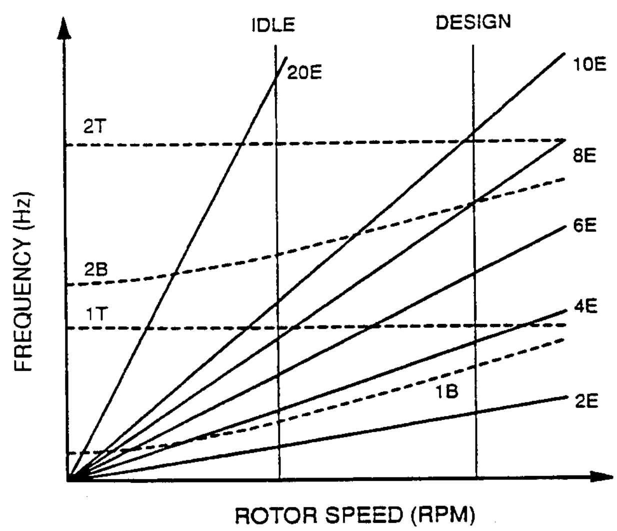
AERO - MECHANICS

PROBLEM:

* Forced response & flutter are significant concerns in the design and development of current & future fans, compressors & turbines



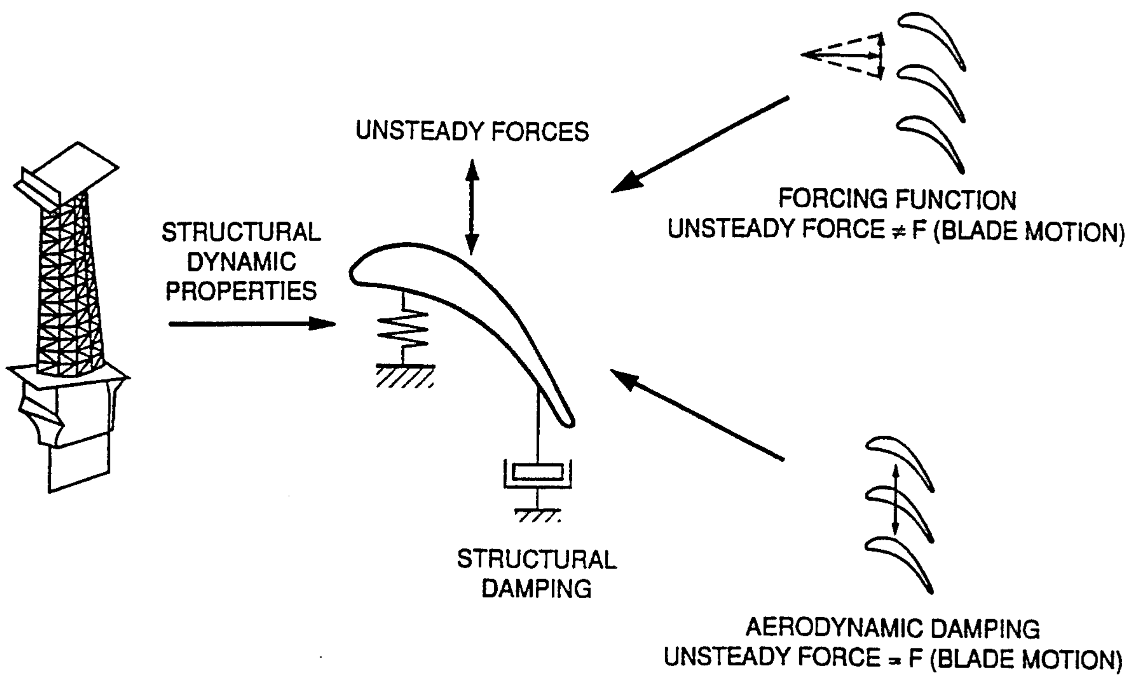
FLUTTER



FORCED RESPONSE

AERO-MECHANICS STATE-OF-THE-ART

Isolated Blade Row



* Every new gas turbine has had at least one blade row or stage with aero-mechanics problems
* Problems discovered & solved through extensive prototype testing & iterative re-design

COST

* Enormous
  * Direct cost of correcting problem
  * Indirect cost of extending development

* **Forcing Functions - Isolated Blade Row**

    * Nonuniform flow field generated by inlet distortion, wakes and/or pressure disturbances from adjacent blade rows

* **Unsteady Aerodynamic Blade Loading & Response**

    * Modeling

        * Small perturbations of a uniform or inviscid nonuniform steady flow

        * Analyses applied in a strip theory approach - quasi-three dimensional

        * Research unsteady 2 & 3-D Euler & Navier-Stokes Codes beginning to be applied

    * Experiments

        * Research turbomachines

            * Fundamental flow physics including model verification & direction

        * Engine compressor & turbine rigs

            * Validity of modeling & significant features

FUTURE

* **Integrated High Performance Turbine Engine Technology (IHPTET) Initiative**

  Goal: Doubling of engine propulsion capability by 2003

  Engine Contractor Response: Advanced Turbine Propulsion Plan (ATPP)

  * Engine configurations needed to achieve IHPTET goals

    Decreased size, weight & frontal area

    Increased thrust/power ratio

    Improved cycle efficiency

  Result

  * Features add significant risk associated with aero-mechanics

  * Man jeopardize plans to meet overall goals

* **Limited DOD Funding Future**

  * **Direct Operating Costs (DOC)**

    * Improved efficiency

    * Improved engine durability

* **Aero-mechanics developments necessary to assure durability of future engines**

TECHNICAL ISSUES

Geometric & Flow Characteristics

* **Drastically different blading configurations needed to meet IHPTET Goals**
    * High speed, thin, low aspect ratio blading
    * Decreased stage-to-stage spacing
    * Higher aerodynamic steady loading
    * Unconventional flow path designs
        * More complex steady aerodynamics
    * Reduced stage weight & stiffness
        * Blisks- decreased structural damping
        * Lightweight - new materials

* **Fans**
    * Wide chord, swept, 3-D hollow & composite blades

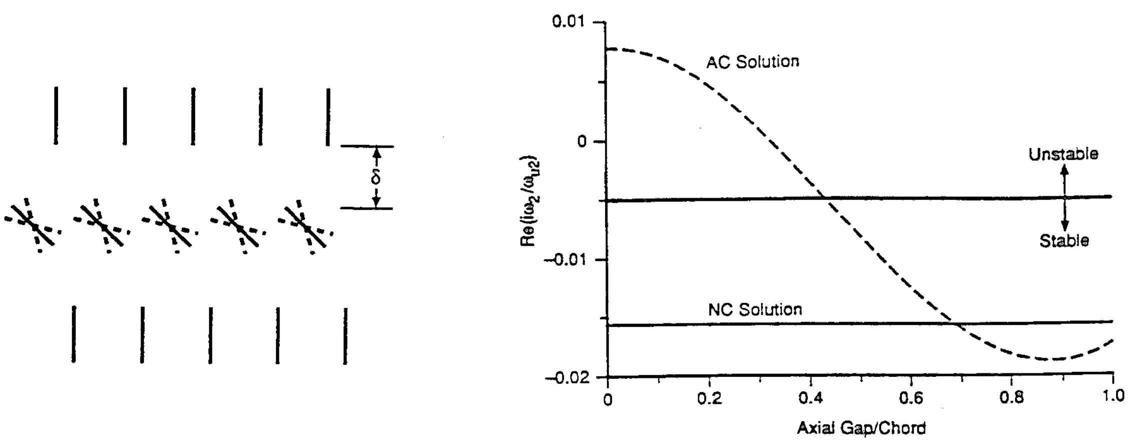
* **Compressors**
    * Decreased spacing, higher aero loadings, low aspect ratio blading, blisks

* **Turbines**
    * Decreased spacing, higher aero loadings, high & low aspect ratio lightweight blading
    * New flutter & forced response problems

RESEARCH NEEDS - FORCING FUNCTIONS

* **Improved understanding of excitations**
    * Off-design - separated flow forcing functions
    * 3-dimensional
    * Near field wakes - fans, compressors & turbines
        * 3- D, low aspect ratio, highly loaded blading, swept blading
    * Multi-stage - closely spaced blade rows
    * Tip vortices

* **Linear & nonlinear interaction of forcing function & blade response generated unsteady aerodynamics**
    * Blade response can be an excitation



* Blade response affects excitations
    * Unsteady aero response generates waves which interact with excitation

* **Tailoring of forcing function to minimize forcing function while maintaining steady aerodynamic performance**

RESEARCH NEEDS - UNSTEADY AERODYNAMICS

* **Blade Row**
    * High incidence off-design with separated flow on airfoil
    * 3-dimensional unsteady aerodynamics
    * Higher order plate-like modes

* **Aerodynamic Damping**
    * Maximize aerodynamic damping

* **Fundamental data needed to verify/direct modeling**
    * Issue is engine data - prediction correlation - not code-to-code correlation
        * May not be able to sort out engine data
        * Research rigs modeling fundamental phenomena

* **Advanced experimental techniques need to be applied and/or developed**
    * Flow solvers predict complete unsteady flow field
    * Data - limited number of point measurements

* **Nonlinear effects**
    * Models consider small perturbations
    * Actual disturbances are finite amplitude
        * Significance of nonlinear effects
    * Gust - oscillating airfoil unsteady aerodynamic interactions

* **Interdisciplinary Unsteady Aerodynamics**

  * **Interacting unsteady aerodynamics - aero-mechanics & performance**

    * Minimize forced response while maintaining or improving steady performance

  * **Interacting unsteady aerodynamics & structures**

    * Complex mode shapes

    * Limit cycle vibrations

SOME FLOW PHYSICS ISSUES

WINCAT October 1993

Ted Okiishi
Mechanical Engineering Department
Iowa State University

Phone: (515) 294-4395
Fax: (515) 294-3261

Some Unsteady Flow Opportunities

- aeromechanical failure avoidance
  (October 1993 J. of Turbomachinery)
- local burnout concerns
  (Roback and Dring 1993)
- compressor recoverability
  (Copenhaver 1993)
- wake ingestion benefits
  (Smith 1993)
- noise minimization
  (Epstein 1994)
- CFD
  (Wisler 1994)
- measurements
  (Alday 1993)

REFERENCES

Alday, J., Osborne, D. J., Morris, M. B. and Ng, W., 1993. "Flow Randomness and Tip Losses in Transonic Rotors." ASME Paper 93-GT-189.

Batson, B. W. and Okiishi, T. H., 1987. "Comparison of Predicted and Measured Axial-Flow compressor Blade-Section Profile Loss." Proceedings of the 1987 Tokyo International Gas Turbine Congress, Vol. II, Gas Turbine Society of Japan, Tokyo, Japan.

Copenhaver, W. W. and Okiishi, T. H., 1993. AIAA Journal of Propulsion and Power 9:281-292.

Denton, J. D., 1993. "Loss Mechanisms in Turbomachines." ASME Journal of Turbomachinery, October.

Halstead, D. E., Okiishi, T. H. and Wisler, D. C., 1990. "Boundary Layer Transition and Separation on a Turbine Blade in a Plane Cascade." AIAA Paper No. 90-2263.

Hansen, J. L. and Okiishi, T. H., 1989. "Rotor Wake Segment Influence on Stator Surface Boundary Layer Development in an Axial-Flow Compressor Stage." AIAA Journal of Propulsion and Power 5:89-94.

Hodson, H. P., Banieghbal, M. R. and Dailey, G. M., 1993. "3-Dimensional Interactions in the Rotor of an Axial Turbine." AIAA Paper No. 93-2255.

Huntsman, I. and Hodson, H. P., 1993. "A Laminar Flow Rotor for a Radial Inflow Turbine." AIAA Paper No. 93-1796.

Kerrebrock, J. L. and Mikolajczak, A. A., 1970. "Intra Stator Transport of rotor Wakes and Its Effect on Compressor Performance." ASME Journal of Engineering for Power 92:359-370.

Roback, R. J. and Dring, R. P., 1993. "Hot Streaks and Phantom Cooling in a Turbine Rotor Passage Part 1 - Separate Effects and Part 2 - Combined Effects and Analytical Modeling." ASME Journal of Turbomachinery. October 1993.

Sharma, O. P., Pickett, G. F. and Ni, R. H., 1992. "Assessment of Unsteady Flows in Turbines." ASME Journal of Turbomachinery 114:19-90.

Sharma, O. P. , Renaud, E., Butler, T. L., Milsaps, K., Dring, R. P. and Joslyn, H. D., 1988. "Rotor-Stator Interaction in Multistage Axial Turbines." AIAA Paper No. 88-3013.

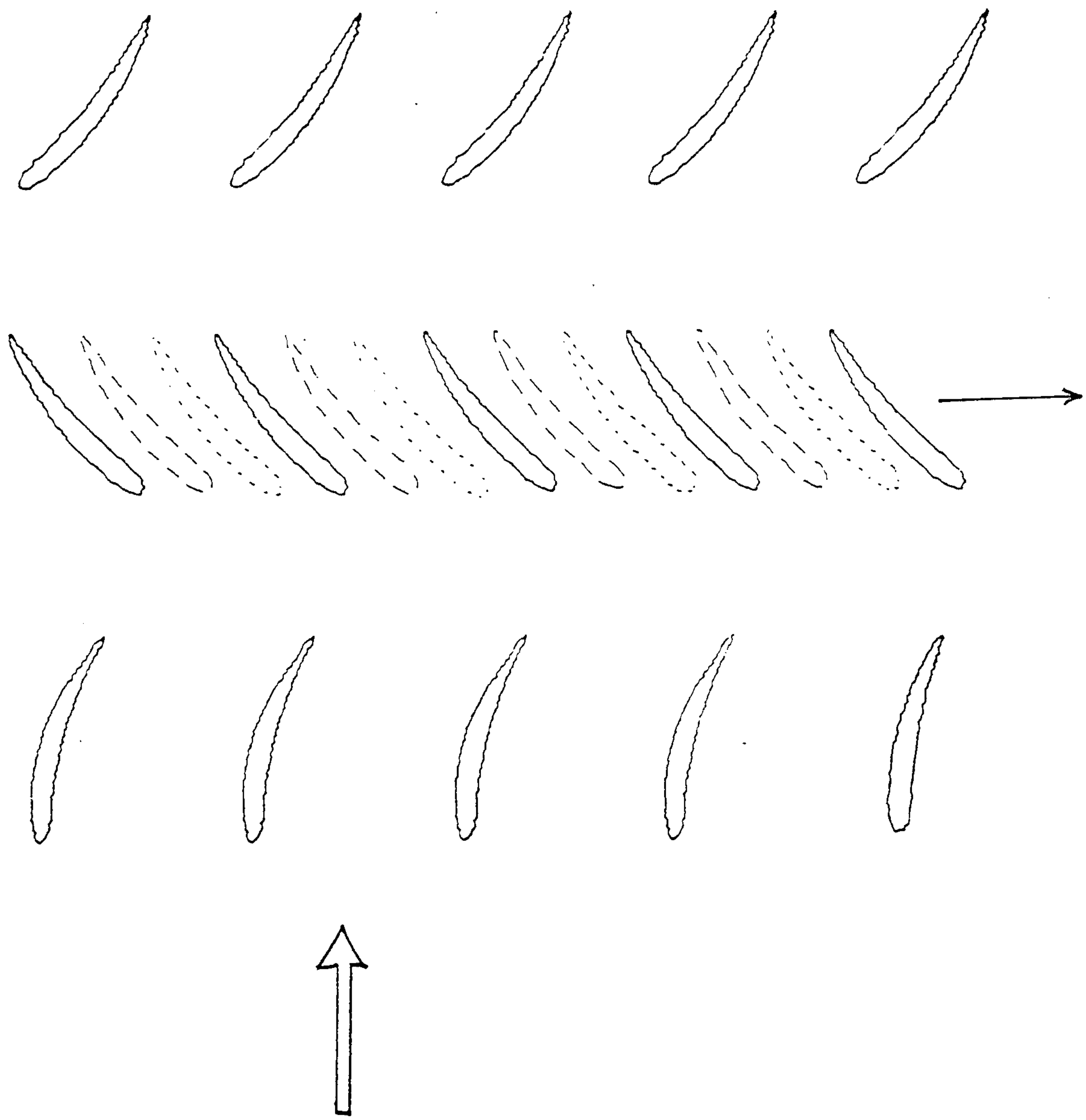
Smith, L. H., Jr., 1993. "Wake Ingestion Propulsion Benefit." AIAA Journal of Propulsion and Power 9:74-82.

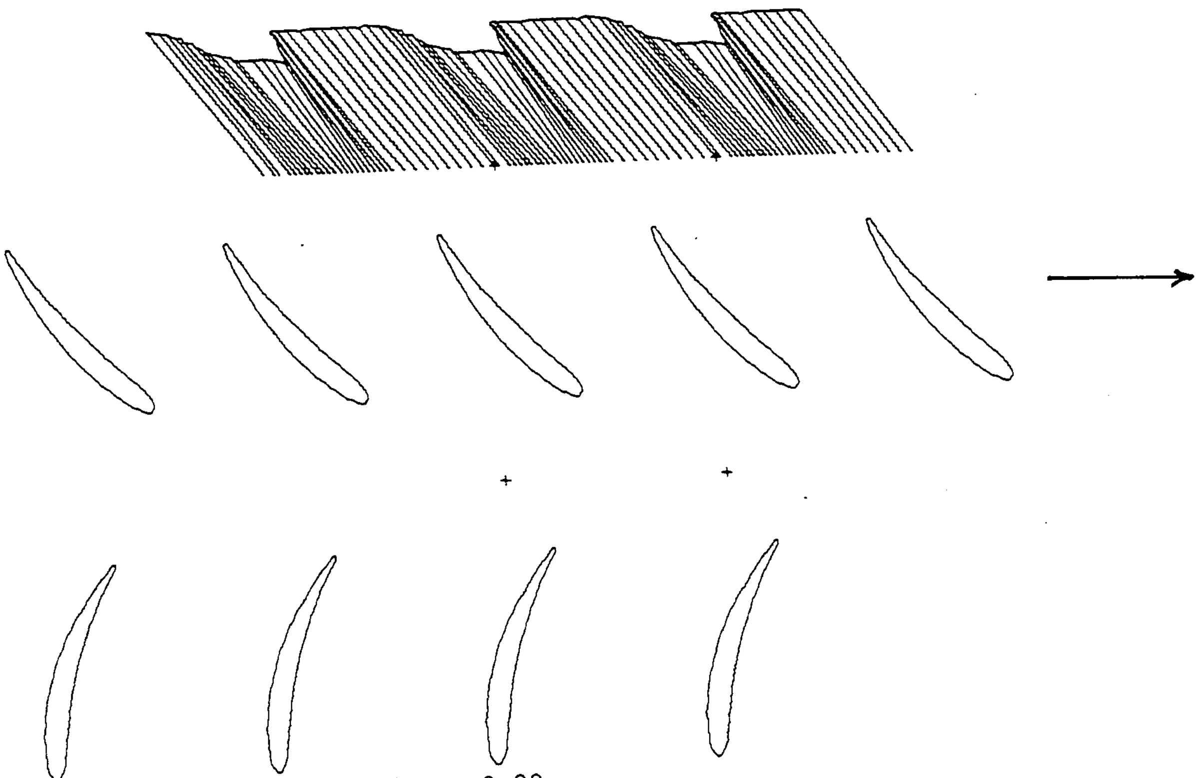
Wagner, J. H., Okiishi, T. H. and Holbrook, G. J., 1979. "Periodically Unsteady Flow in an Imbedded Stage of a Multistage, Axial-Flow Turbomachine." ASME Journal of Engineering for Power 101:42-51.

Wennerstrom, A. J., 1991. "A Review of Predictive Efforts for Transport Phenomena in Axial Flow Compressors." ASME Journal of Turbomachinery 113:175-179

Wisler, D, C., Bauer, R. C. and Okiishi, T. H., 1987. "Secondary Flow, Turbulent Diffusion and Mixing in Axial-Flow Compressors." ASME Journal of Turbomachinery 109:445-482.

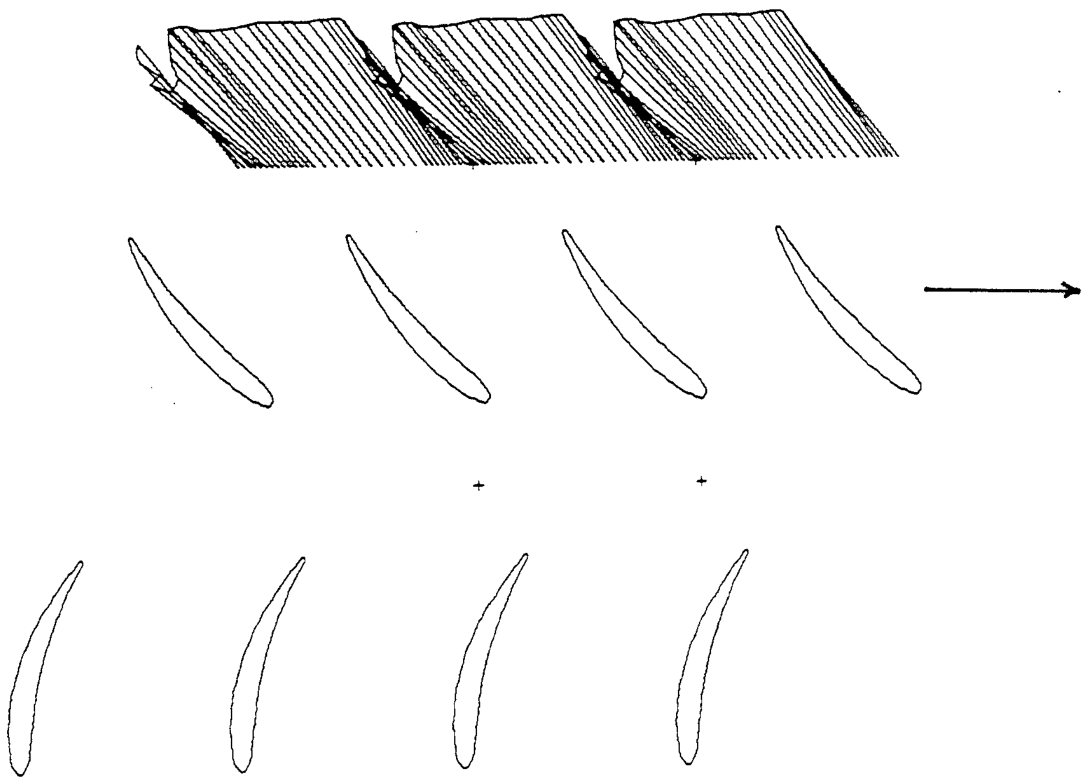
Zierke, W. C. and Okiishi, T. H., 1982. "Measurement and Analysis of Total-Pressure Unsteadiness Data from an Axial-Flow Compressor Stage." ASME Journal of Engineering for Power 104:479-488.



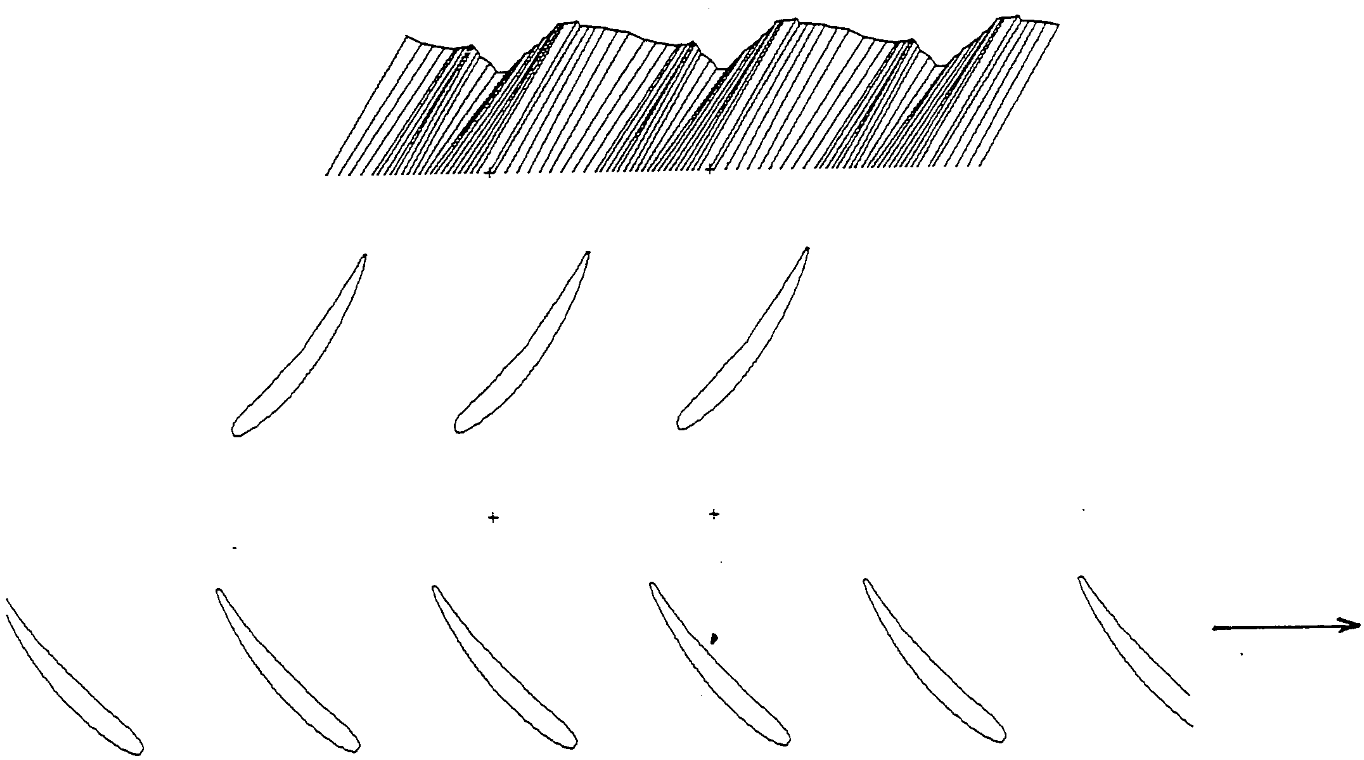


(a) $YO_R/S_R = 0.00$

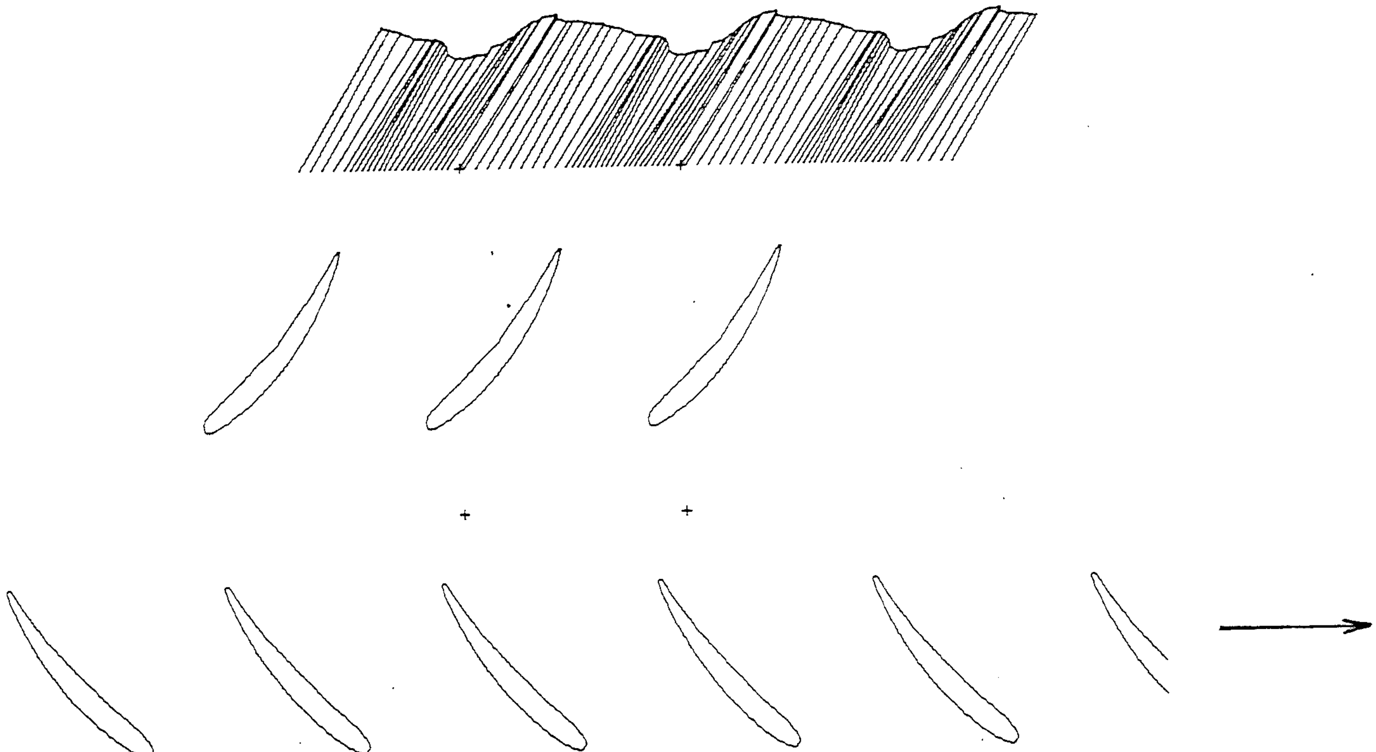
Wagner 1979
Zierke 1983



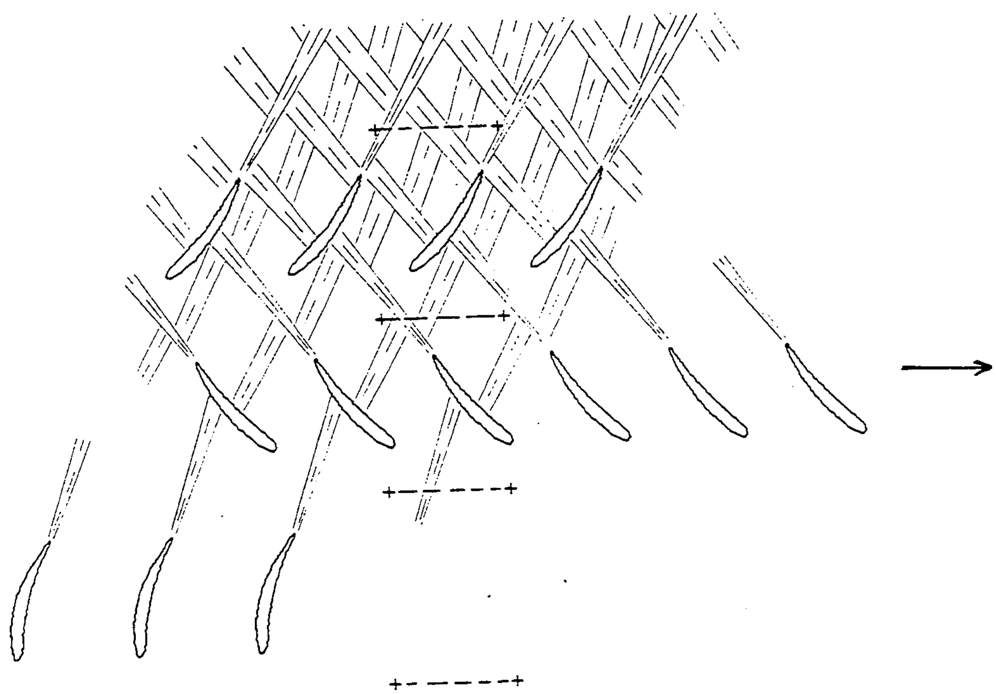
(e) $YO_R/S_R = 0.69$



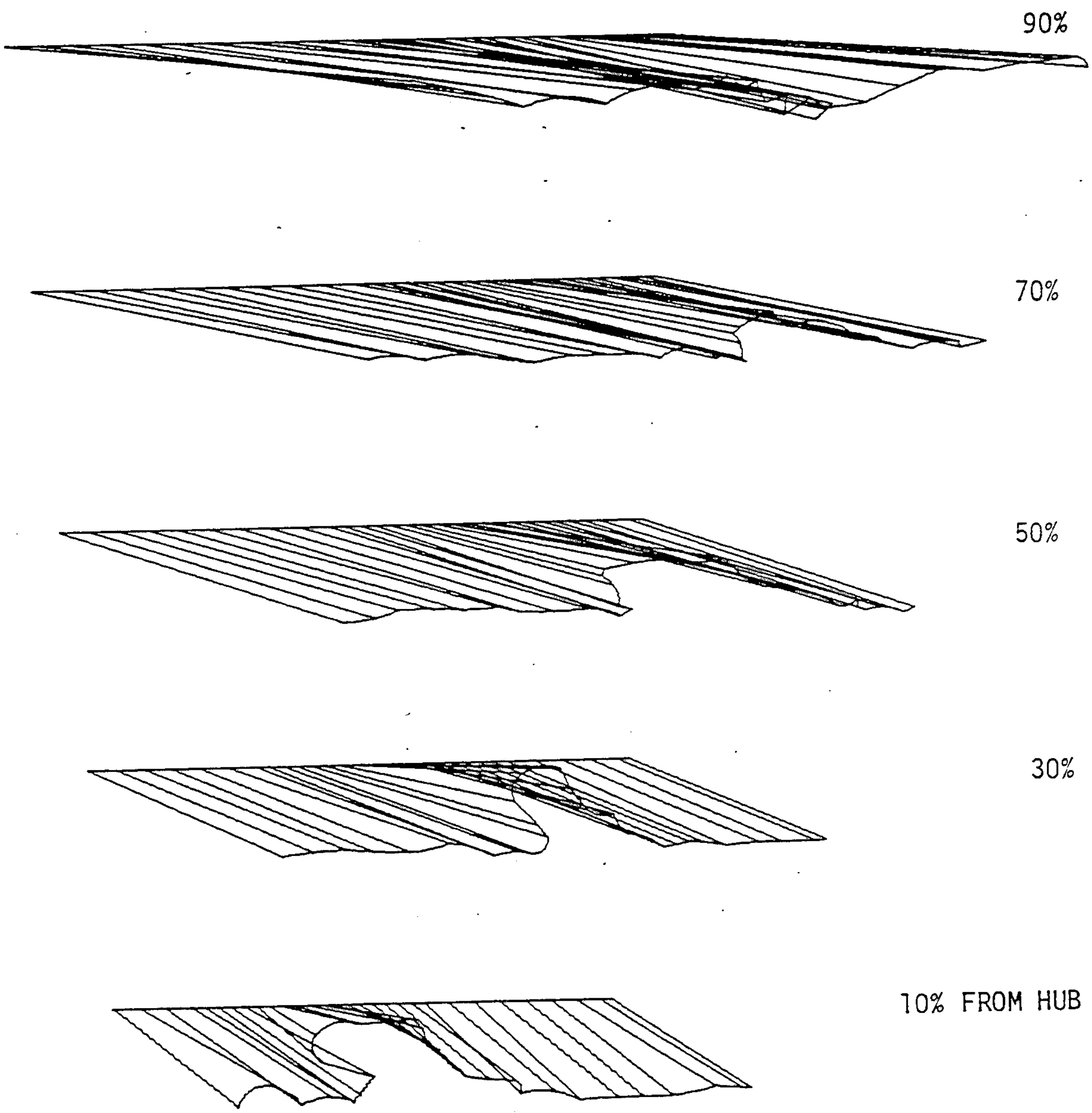
(a) $YO_R/S_R = 0.00$



(b) $YO_R/S_R = 0.17$

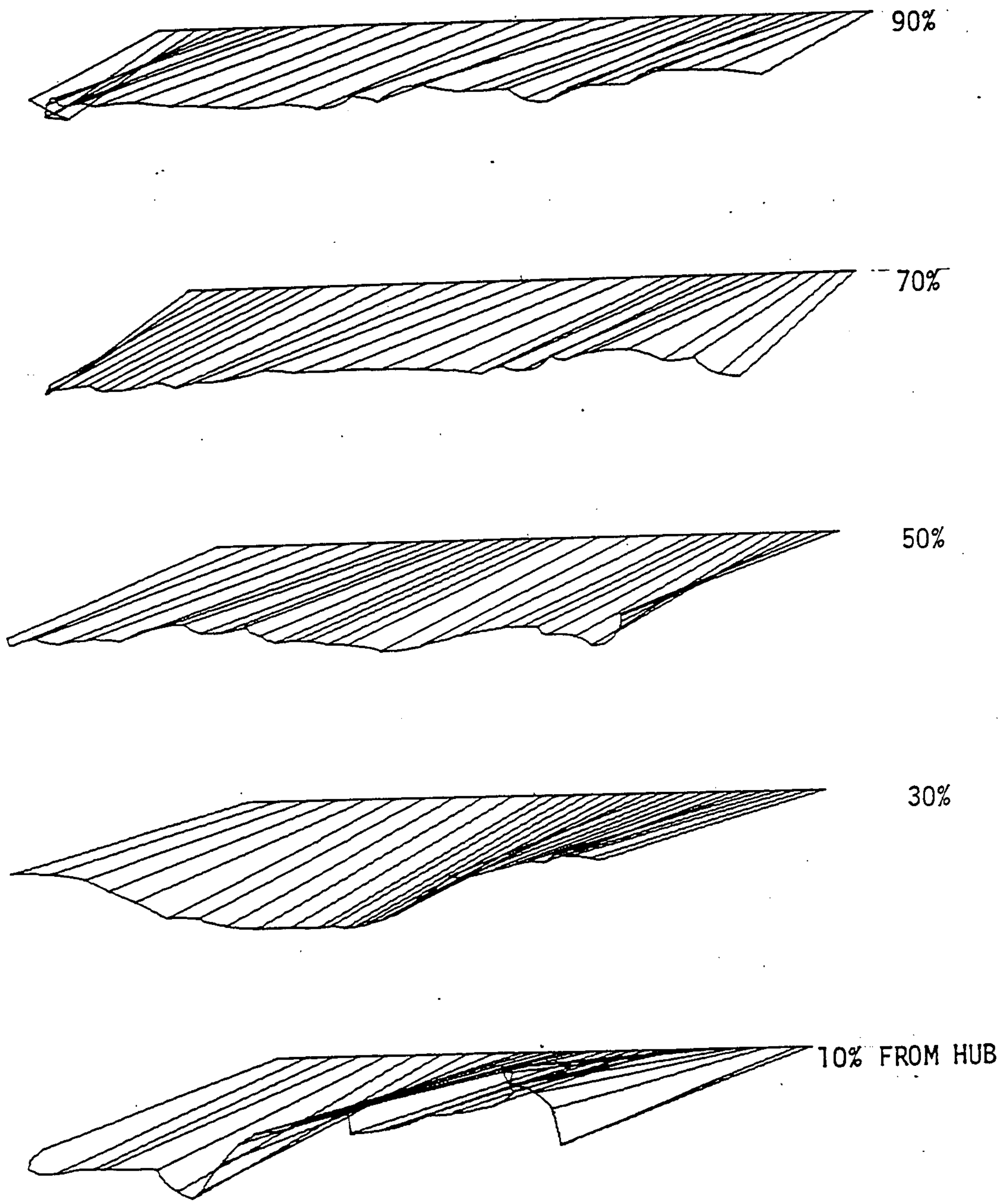


Wagner 1979
Zierke 1983

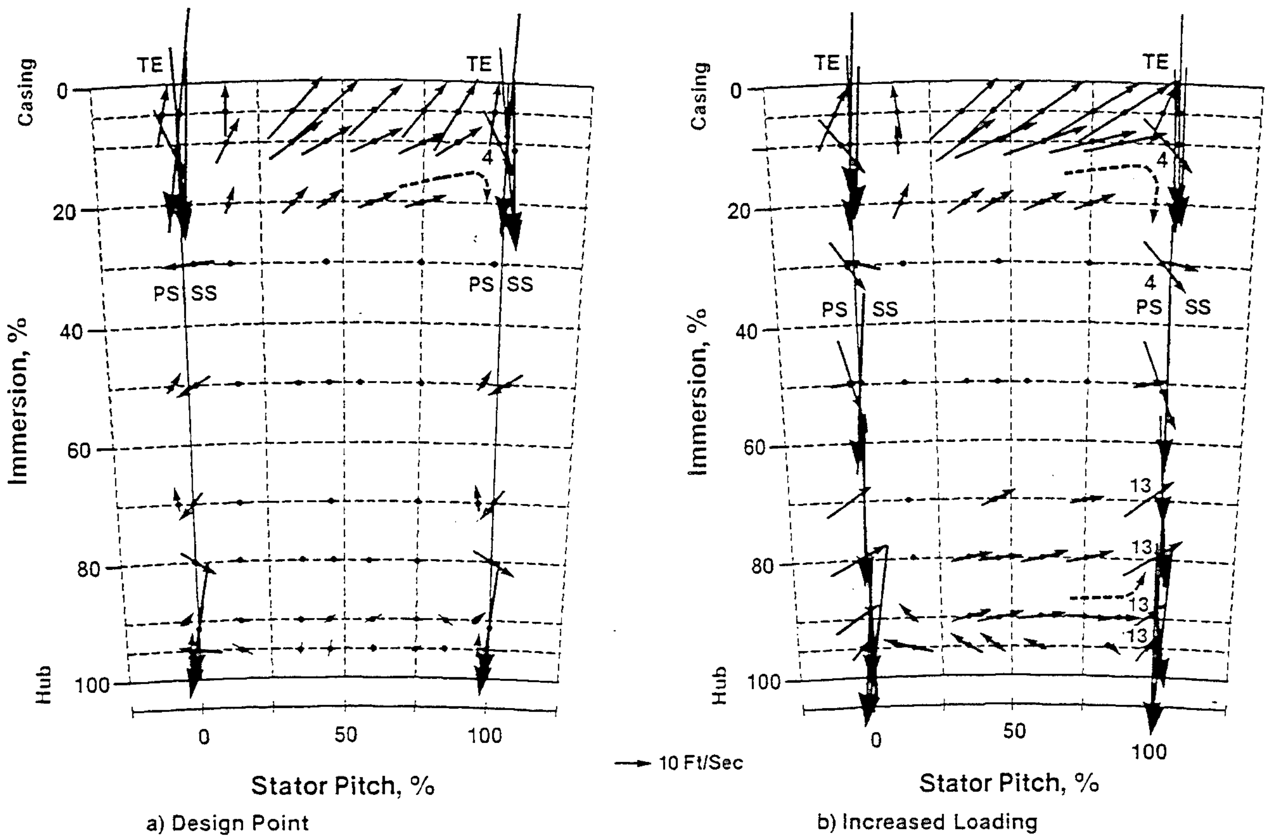


Hub-to-tip variation of first rotor relative exit flow.

Wagner 1979
Zierke 1983

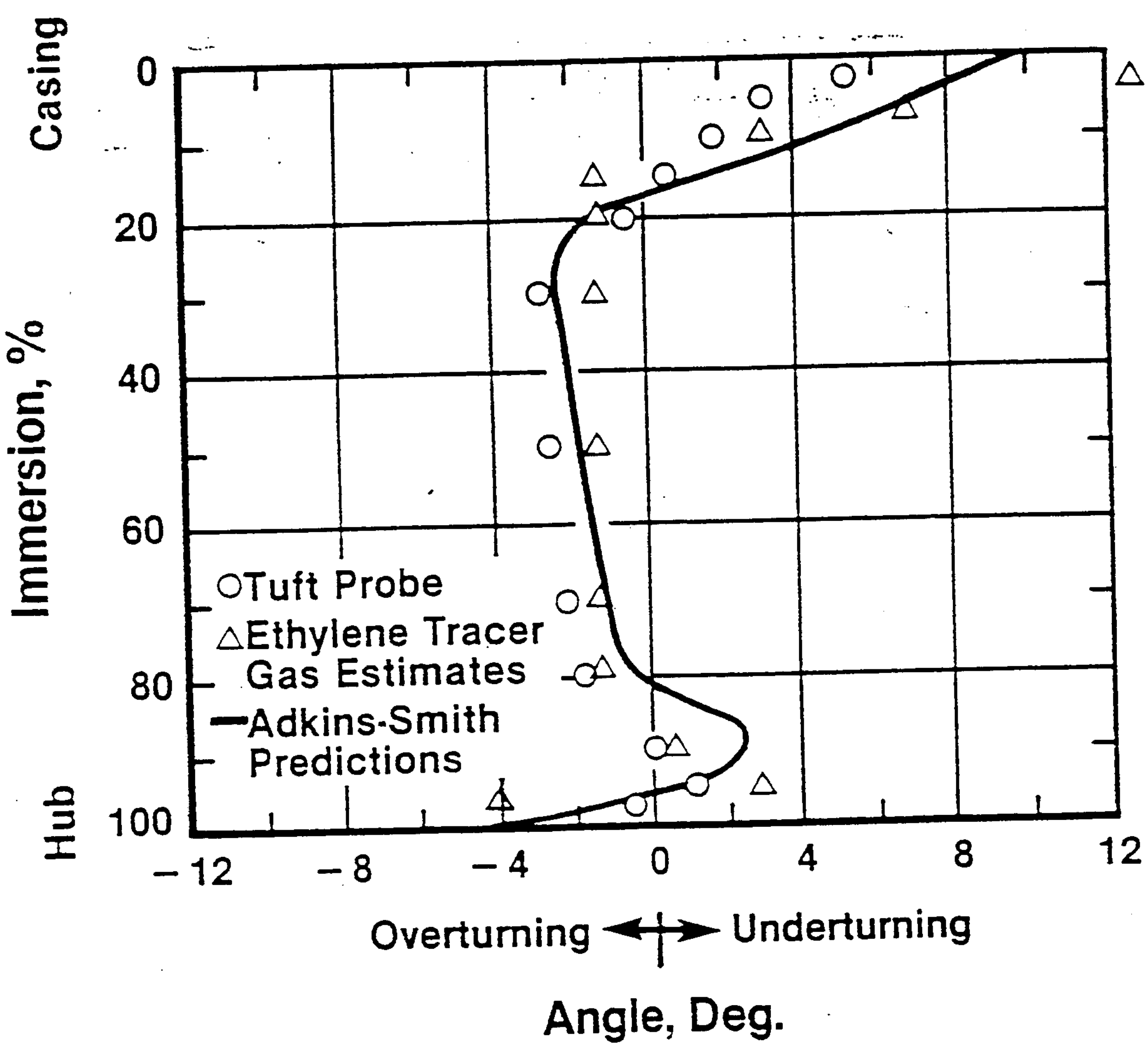


Hub-to-tip variation of first stator exit flow,



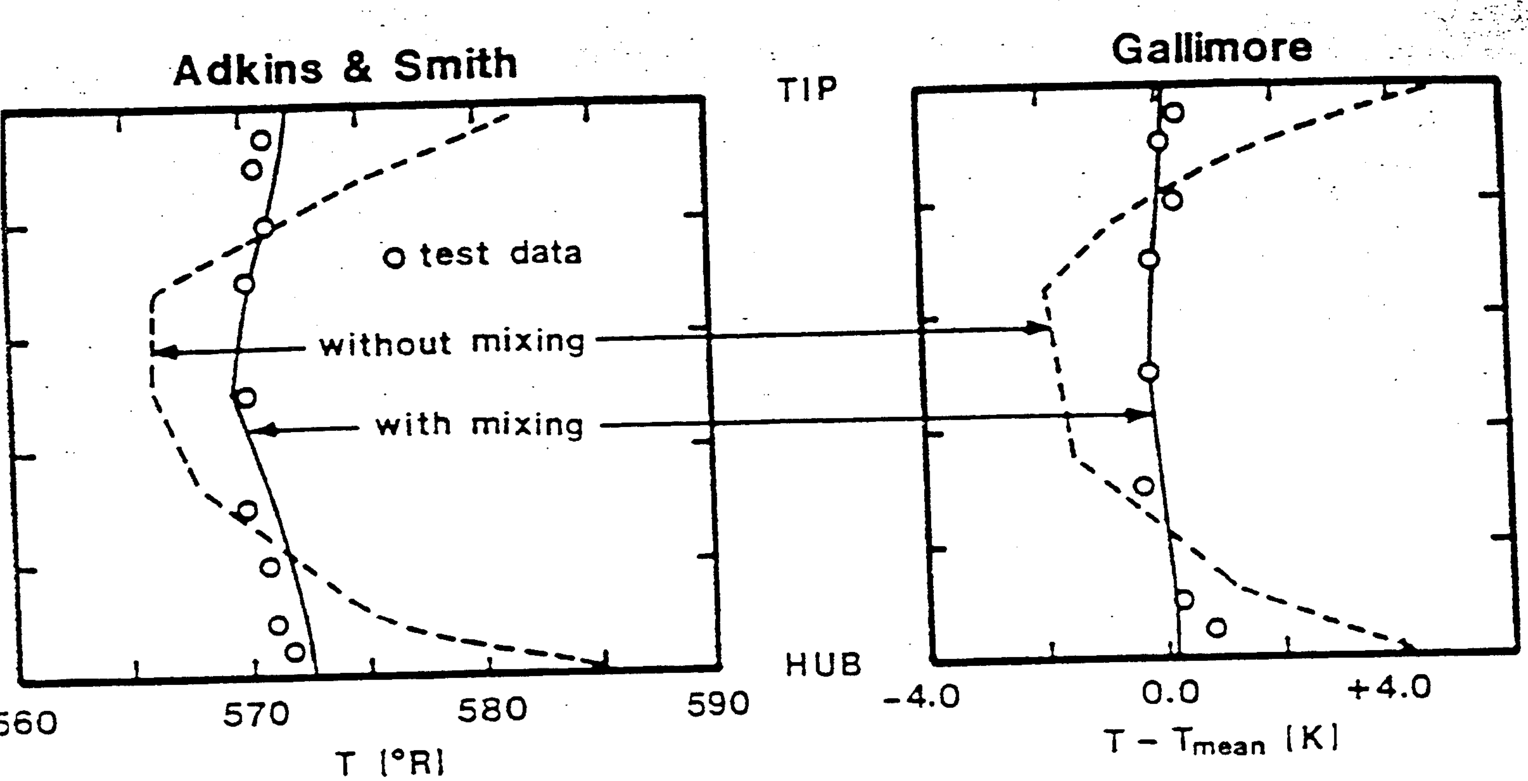
Secondary flow velocity vectors from hot-wire measurements at Stator 3 exit (plane 4.0).

Wisler 1987

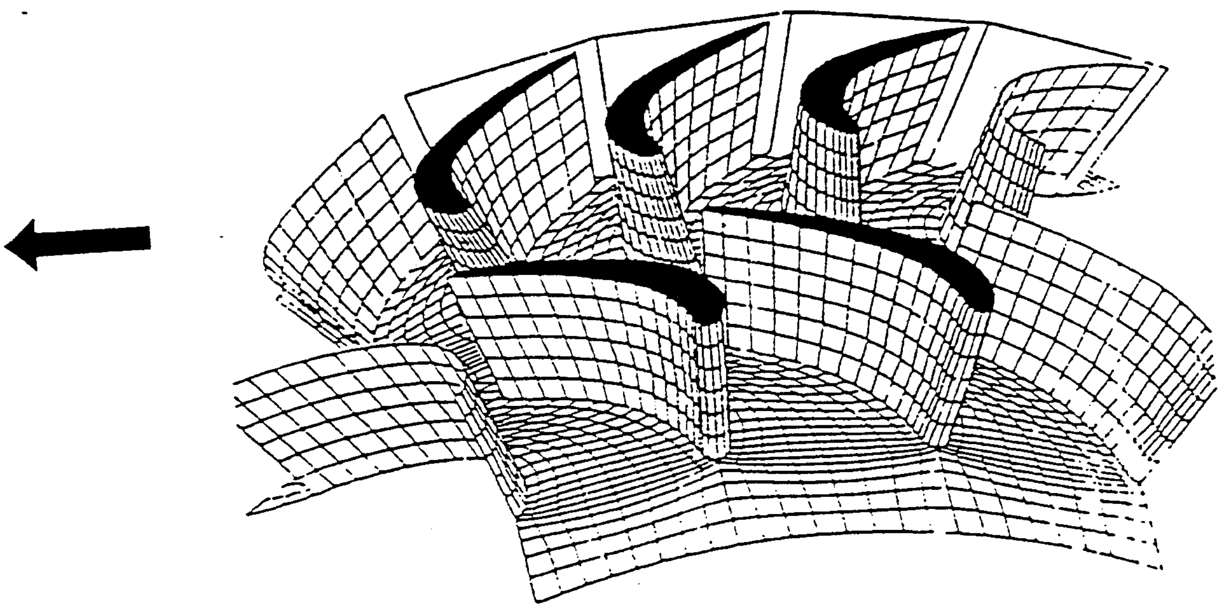


Radial variation of under/overturning at Stator 3 exit.

Wisler 1987



Wennerstrom 1991



Sharma 1992 and 1988

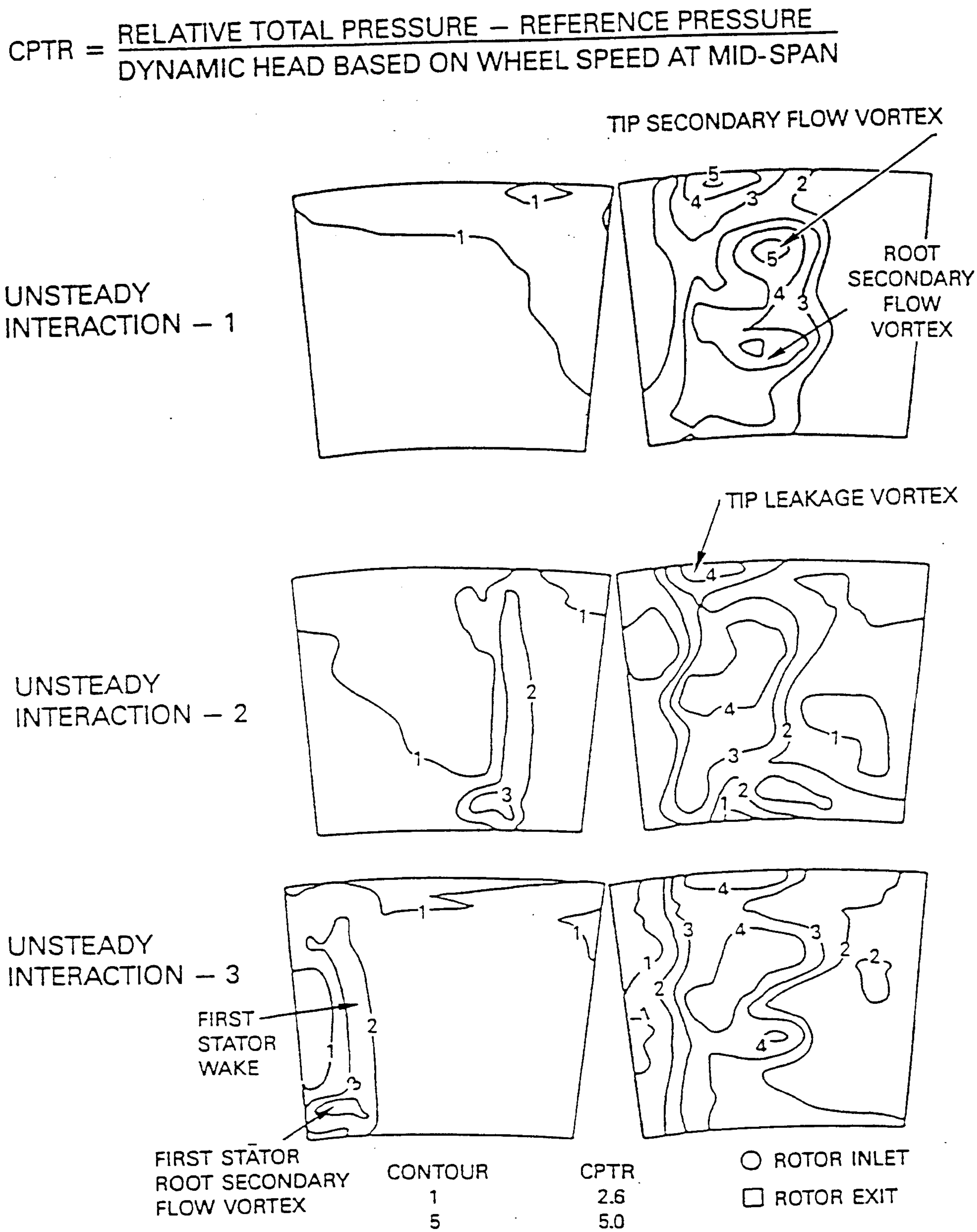


Fig. 6 Secondary flow structures downstream of a rotor (Sharma et al., 1988) obtained from unsteady measurements show large variation in their size, indicating effects of upstream stator wakes

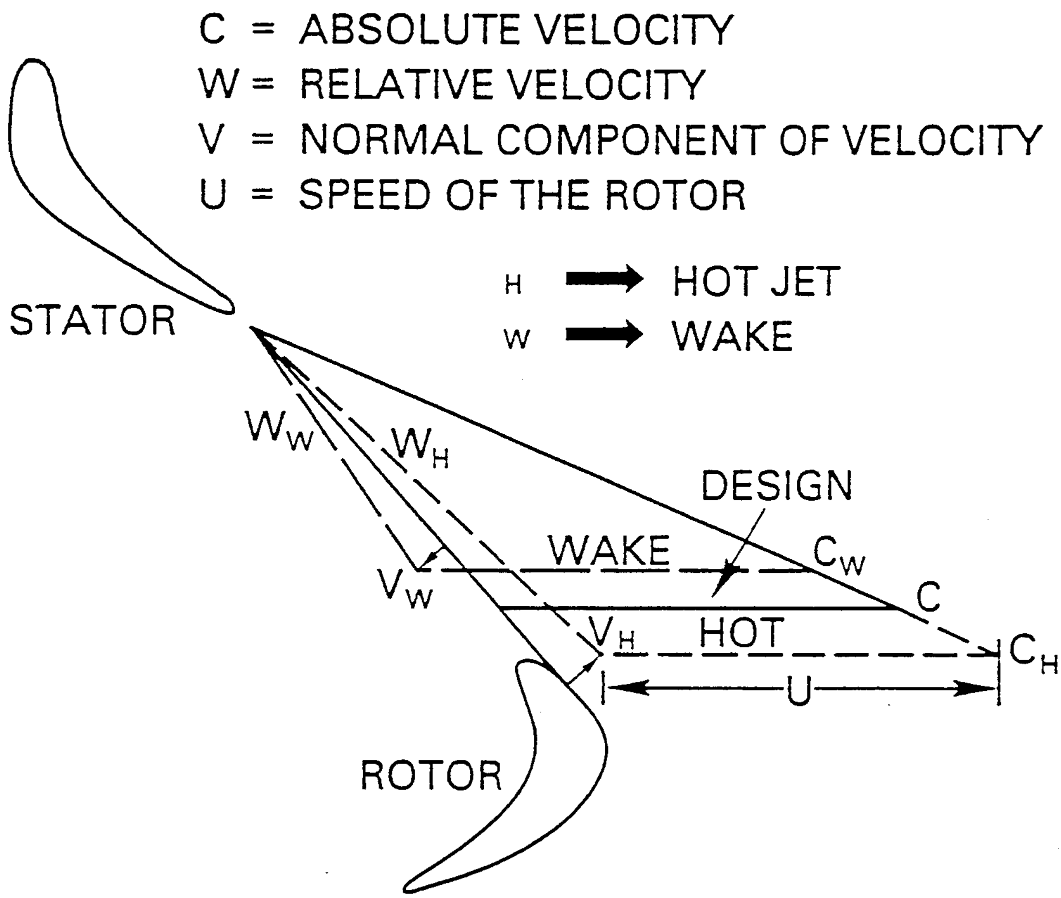


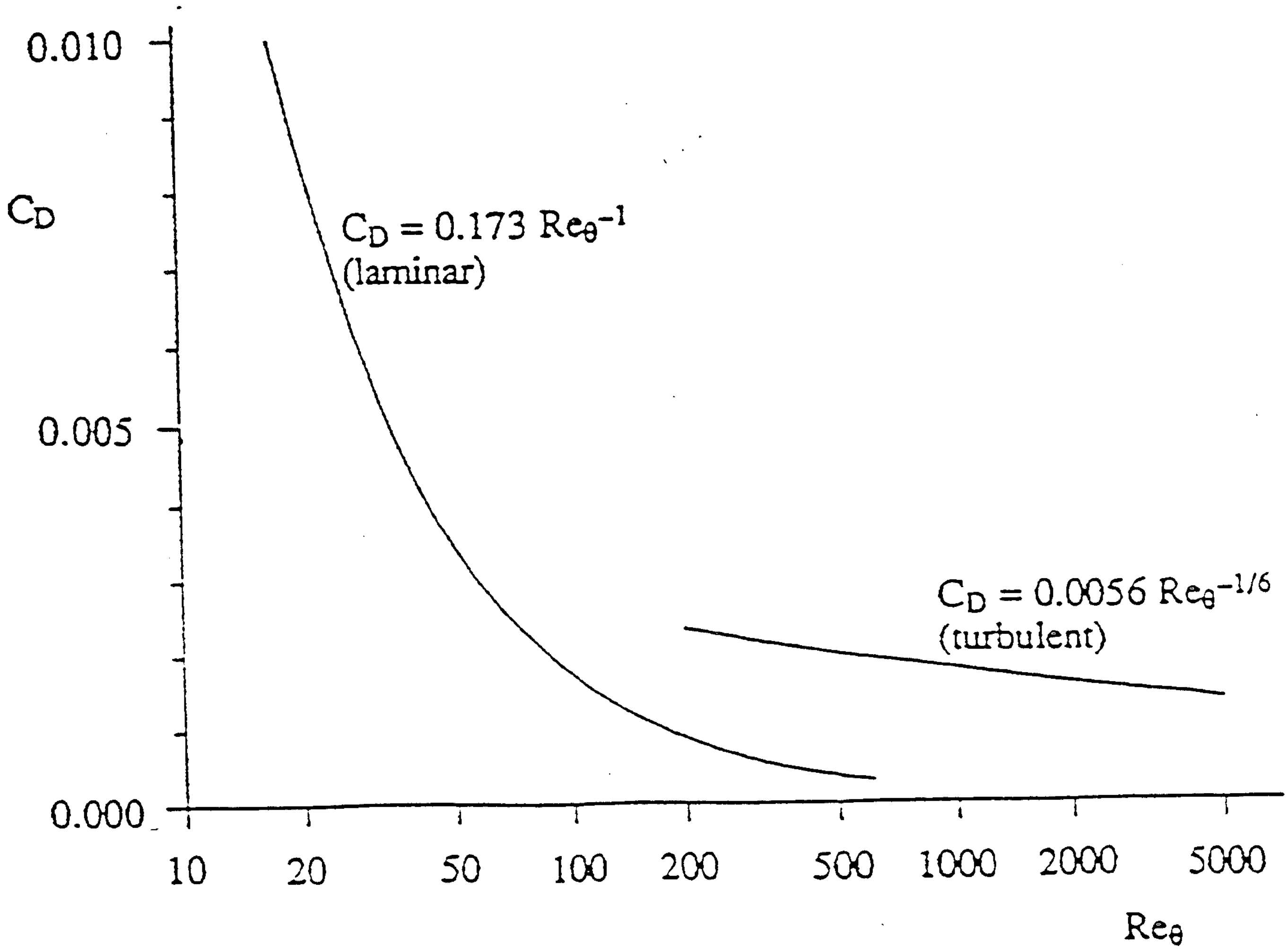
Fig. 4 Wakes and hot jets from upstream stators induce preferential flow migration toward the suction and pressure sides of the downstream rotors (Kerrebrock and Mikolajczak, 1970)

Sharma 1992 and 1988

- radial transport
- circumferential transport
- loss operation

$$\zeta_s = 2 \sum \frac{C_s}{p \cos \alpha_{ref}} \int_0^1 C_d \left(\frac{V_o}{V_{ref}}\right)^3 d(x/C_s)$$

Denton 1993



DISSIPATION COEFFICIENT FOR LAMINAR AND TURBULENT BOUNDARY LAYERS

Denton 1993

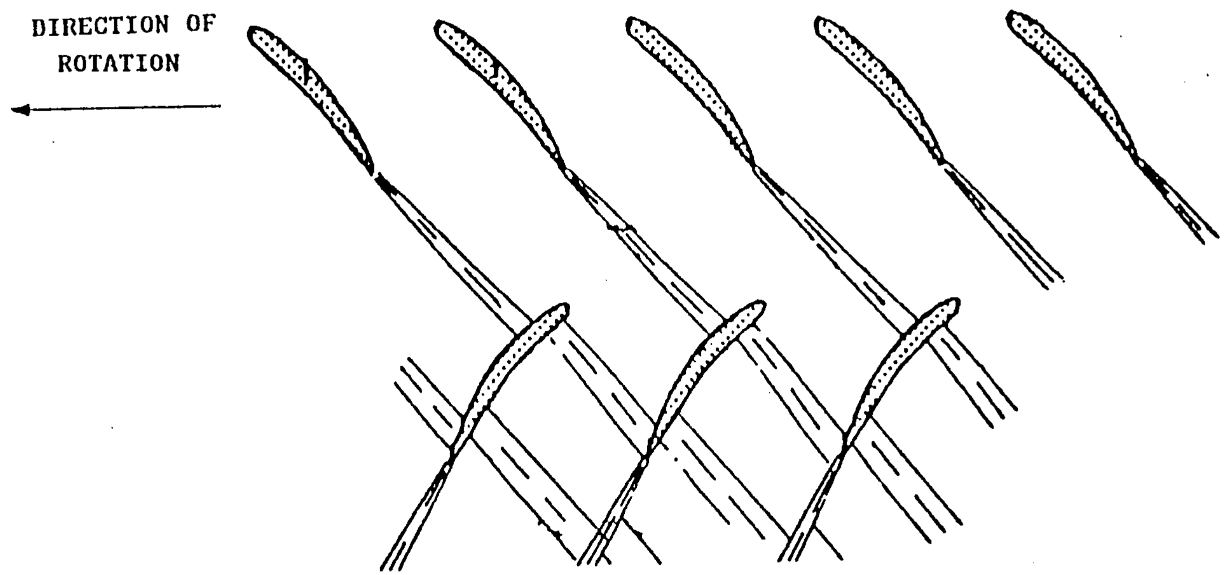
Allison
GAS TURBINE DIVISION
General Motors Corporation
P.O. Box 420
Indianapolis, Indiana 46206-0420

GM

ILLUSTRATION OF TRANSPORTED WAKE SEGMENTS

DATE

CHART NO.



Hansen 1989

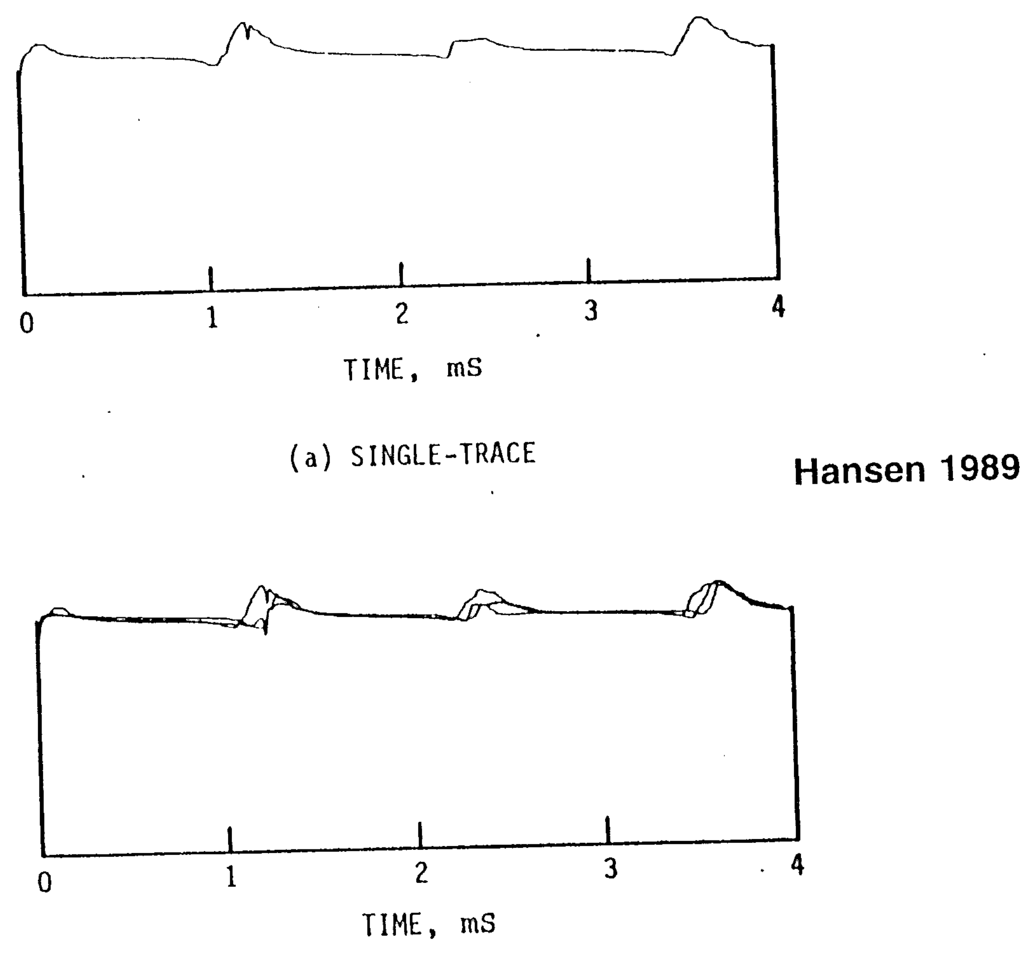
Allison
GAS TURBINE DIVISION
General Motors Corporation
P.O. Box 420
Indianapolis, Indiana 46206-0420

SUCTION SURFACE HOT-FILM OSCILLOGRAM

10% CHORD

DATE

CHART NO.



(b) MULTIPLE-TRACE

GT-8040-1
(4-84)

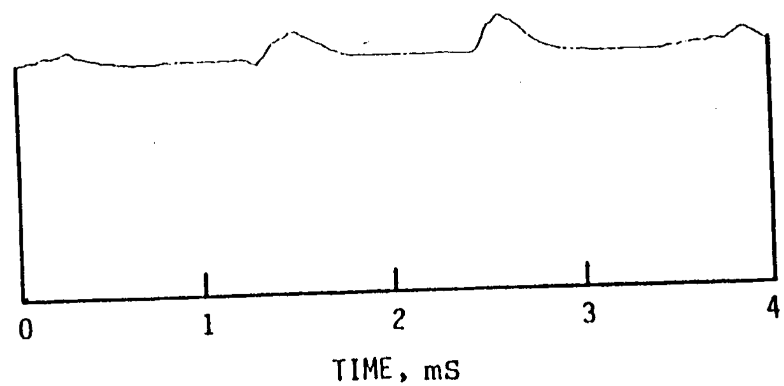
Allison
GAS TURBINE DIVISION
General Motors Corporation
P.O. Box 420
Indianapolis, Indiana 46206-0420

GM

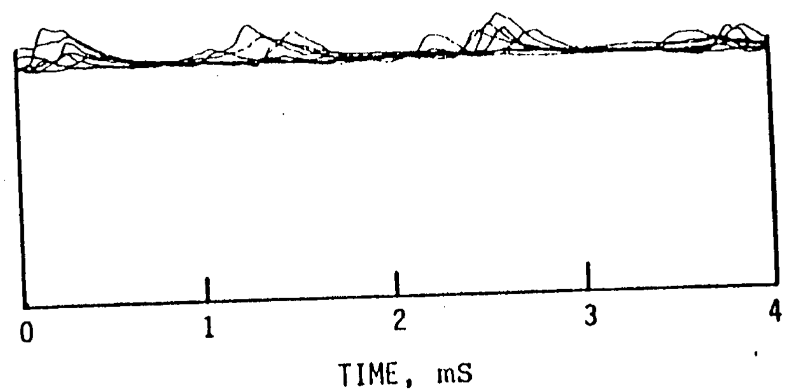
SUCTION SURFACE HOT-FILM OSCILLOGRAM

35% CHORD

CHART NO.



(a) SINGLE-TRACE



(b) MULTIPLE-TRACE

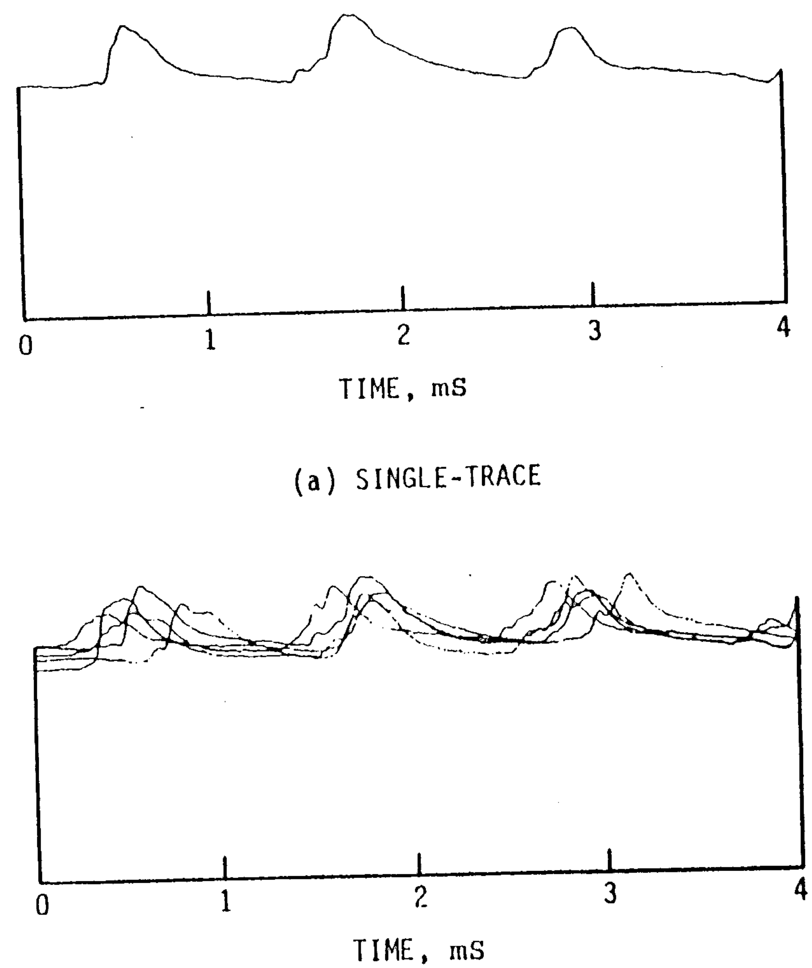
Allison
GAS TURBINE DIVISION
General Motors Corporation
P.O. Box 420
Indianapolis, Indiana 46206-0420

DATE

CHART NO.

SUCTION SURFACE HOT-FILM OSCILLOGRAM

60% CHORD



(a) SINGLE-TRACE

(b) MULTIPLE-TRACE

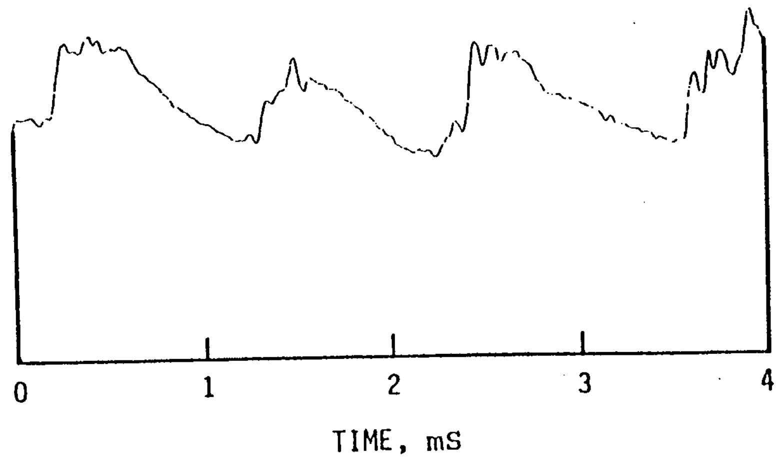
Allison
GAS TURBINE DIVISION
General Motors Corporation
P.O. Box 420
Indianapolis, Indiana 46206-0420

SUCTION SURFACE HOT-FILM OSCILLOGRAM

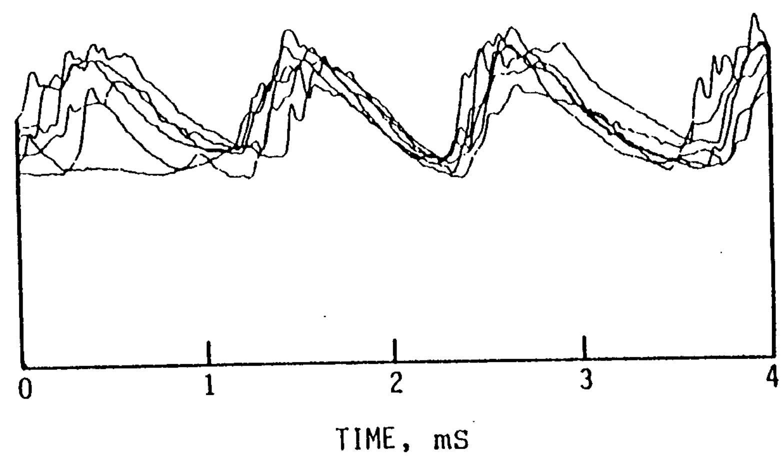
85% CHORD

DATE

CHART NO.



(a) SINGLE-TRACE



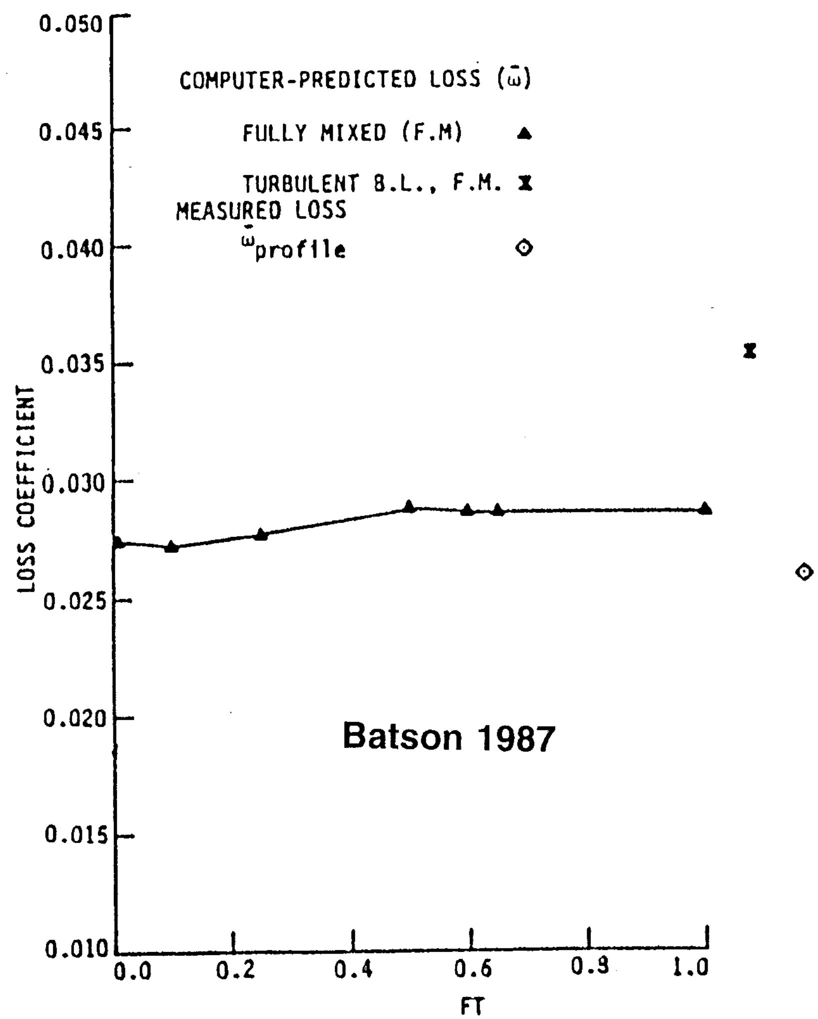
(b) MULTIPLE-TRACE

COMPARISON OF PREDICTED AND MEASURED VALUES OF LOSS COEFFICIENT

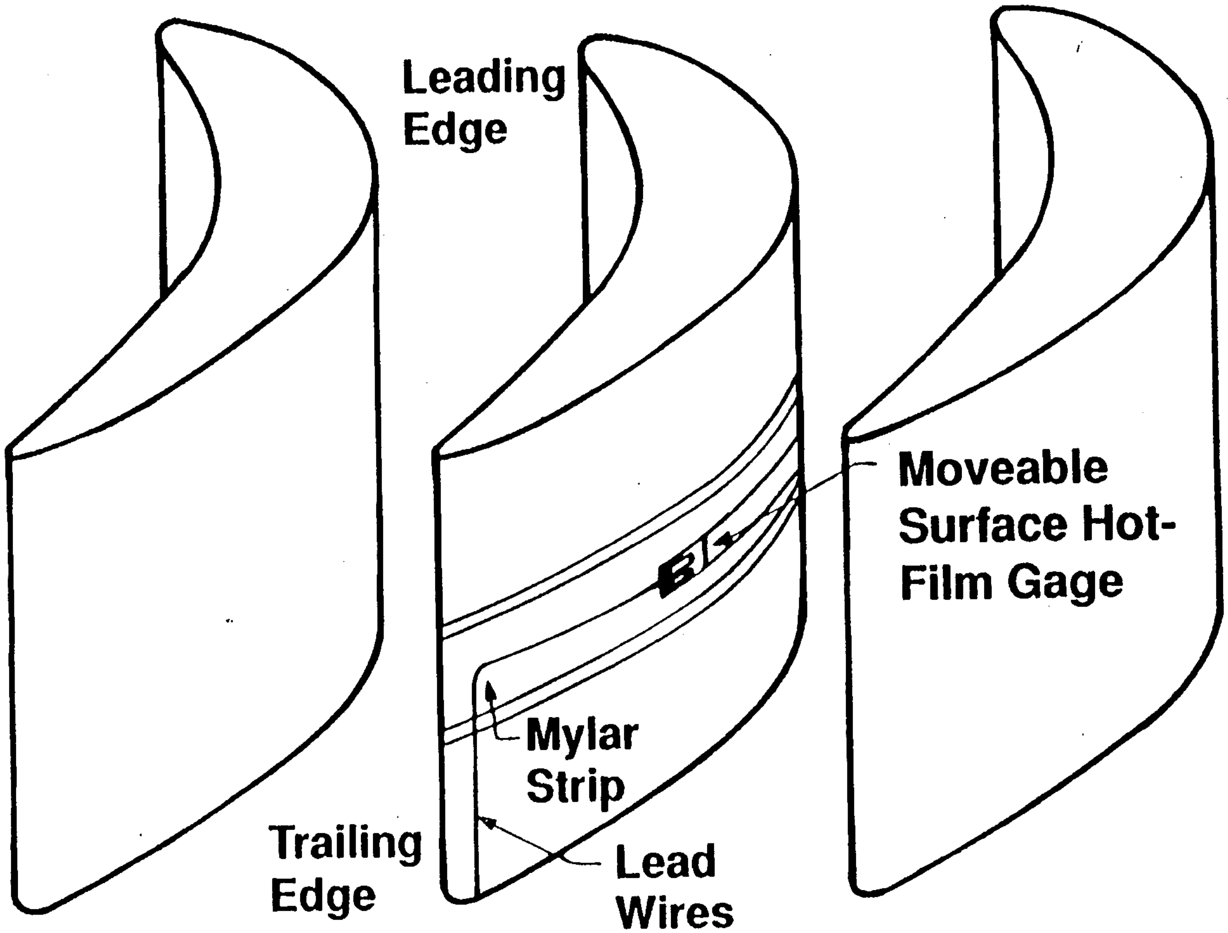
DATE

CHART NO.

LOW-SPEED STATOR



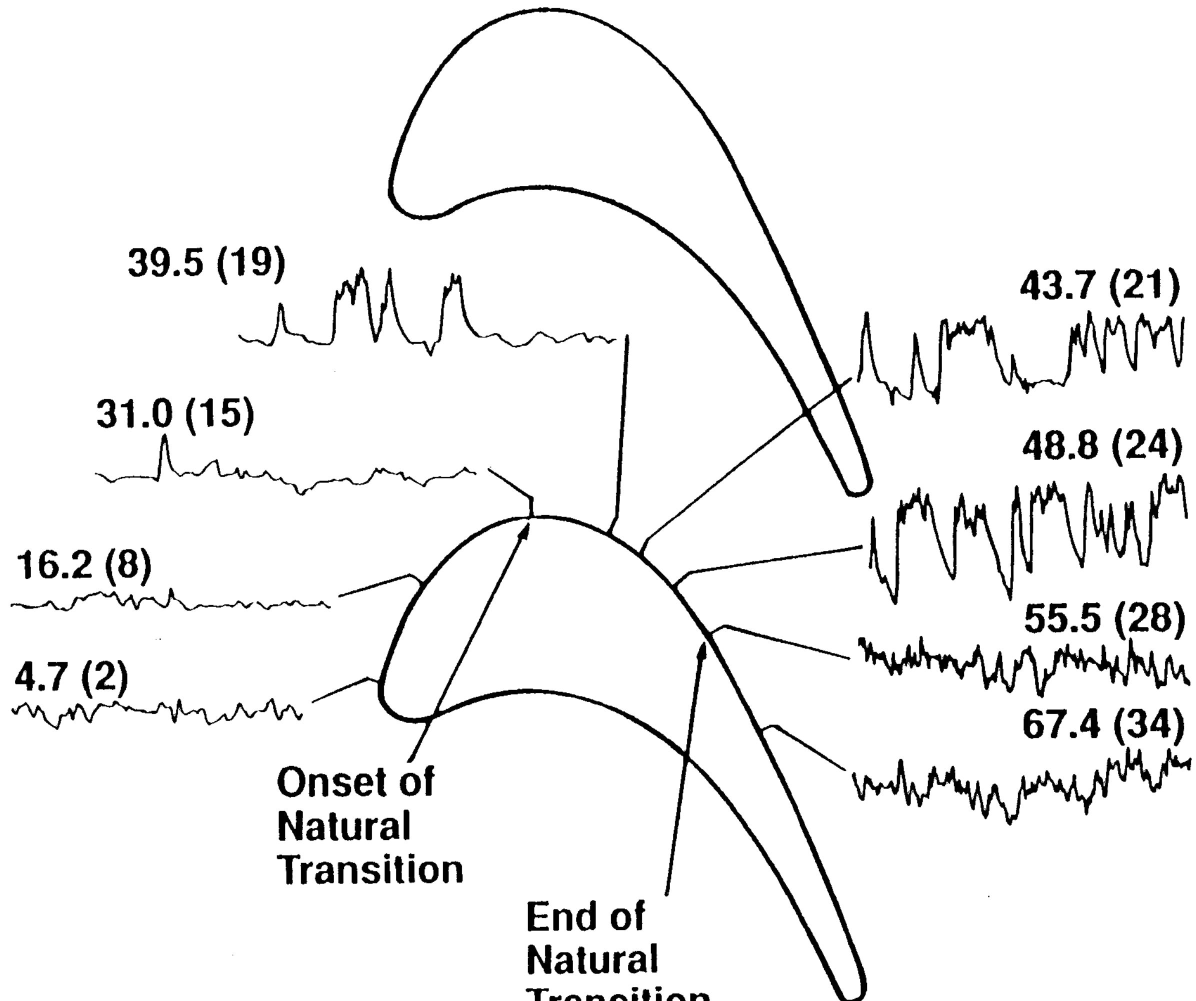
Surface Hot-Film Gage Mounting Technique



Halstead 1990

Selected Hot–Film Traces

Re = 700,000 Tu = 6.4%



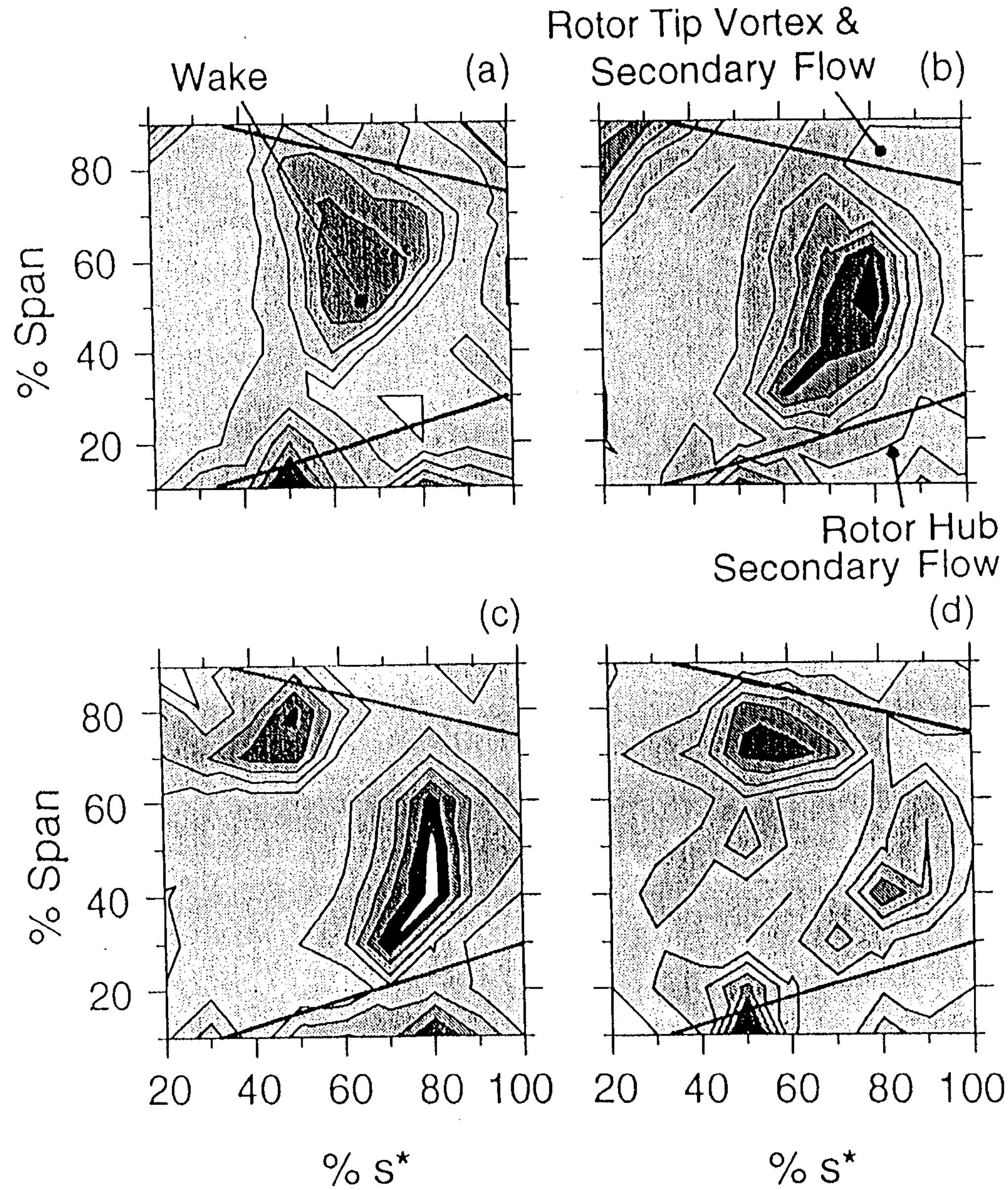
Halstead 1990

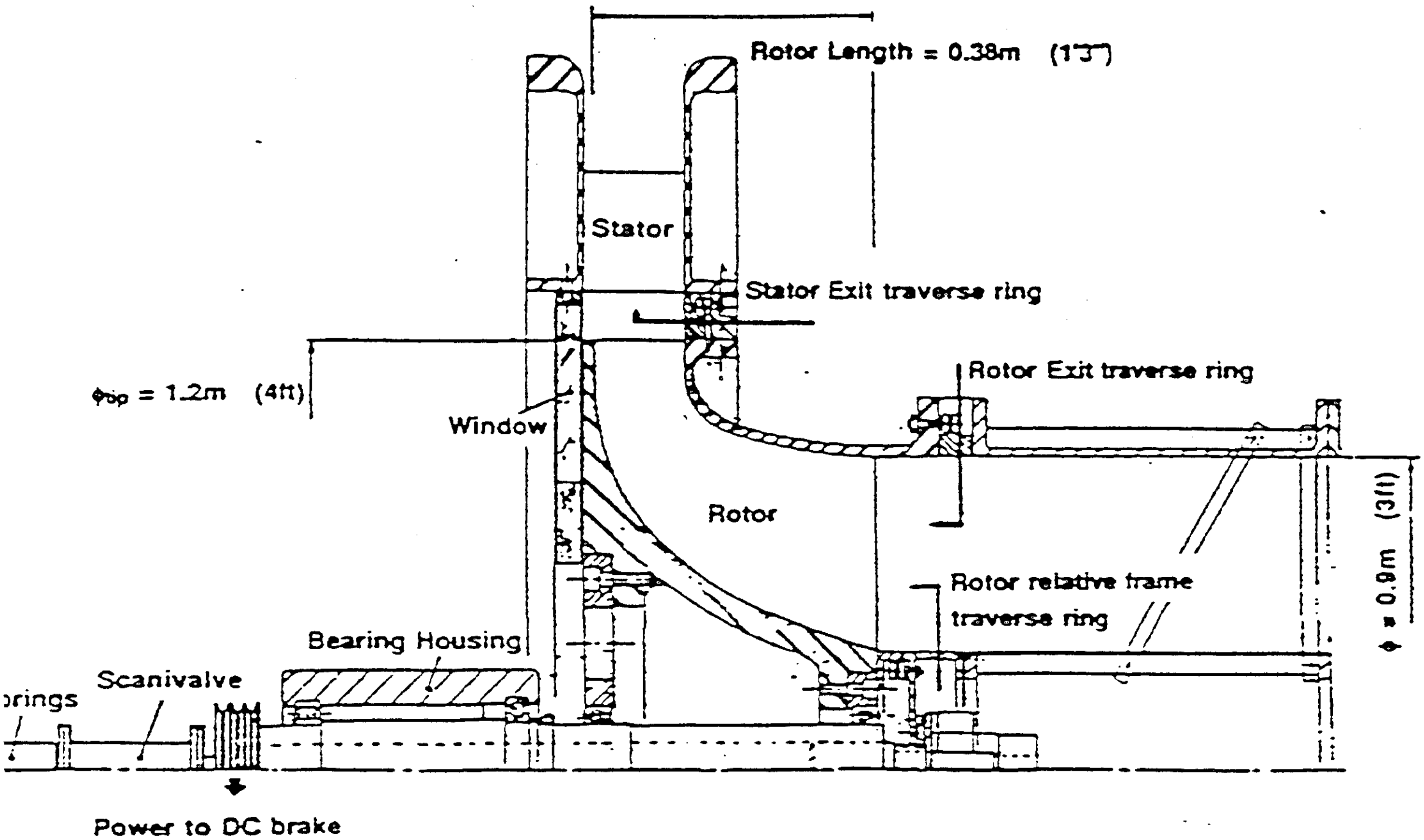
INSTANTANEOUS SUCTION SURFACE FLOW

INSTANTANEOUS
$<\tau_w(s,z,t)> - <\tau_w(s,z,)>_{min}$;

(a) $t/\tau = 1/8$,
(b) $t/\tau = 3/8$,
(c) $t/\tau = 5/8$,
(d) $t/\tau = 7/8$

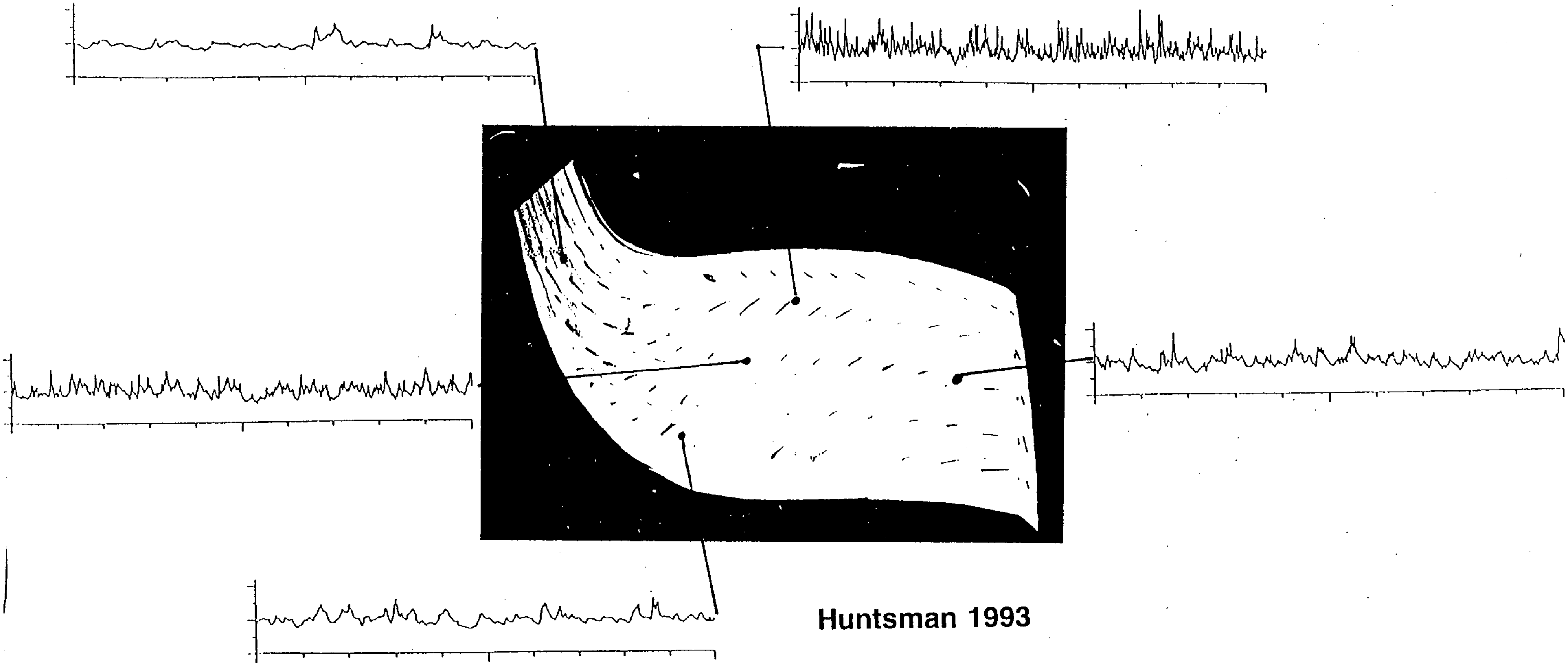
Hodson 1993



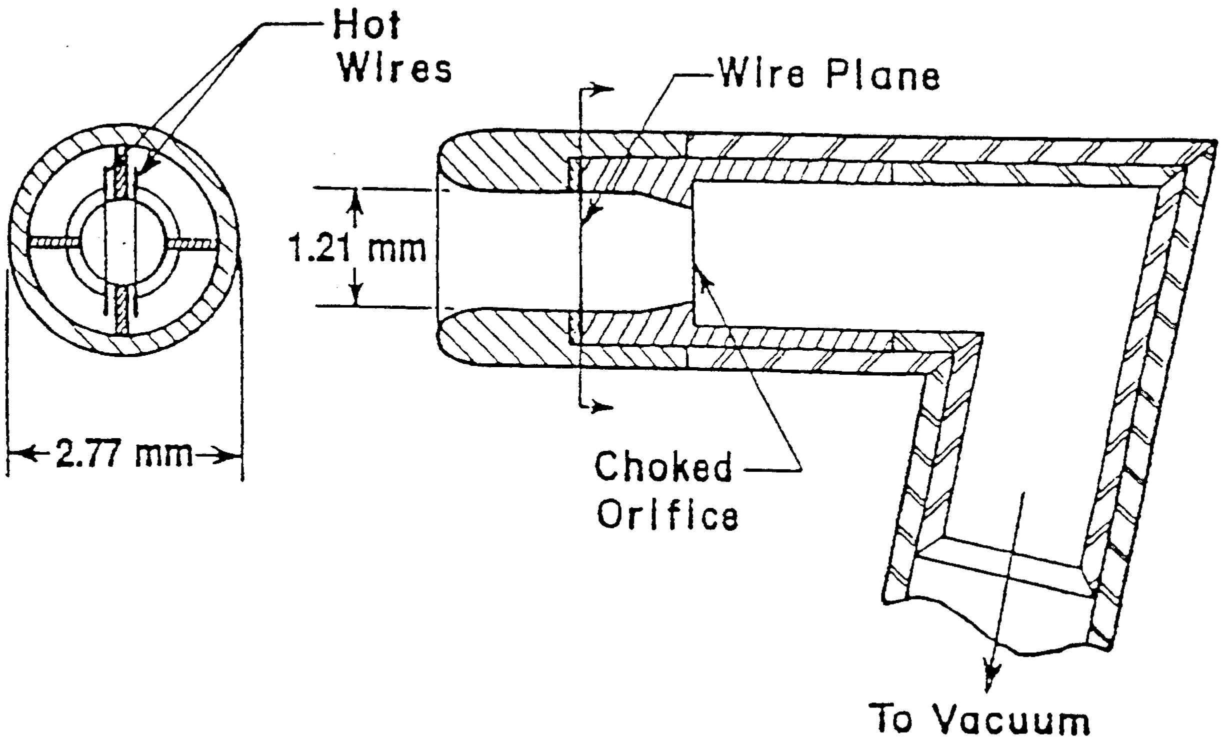


Huntsman 1993

RADIAL INFLOW TURBINES

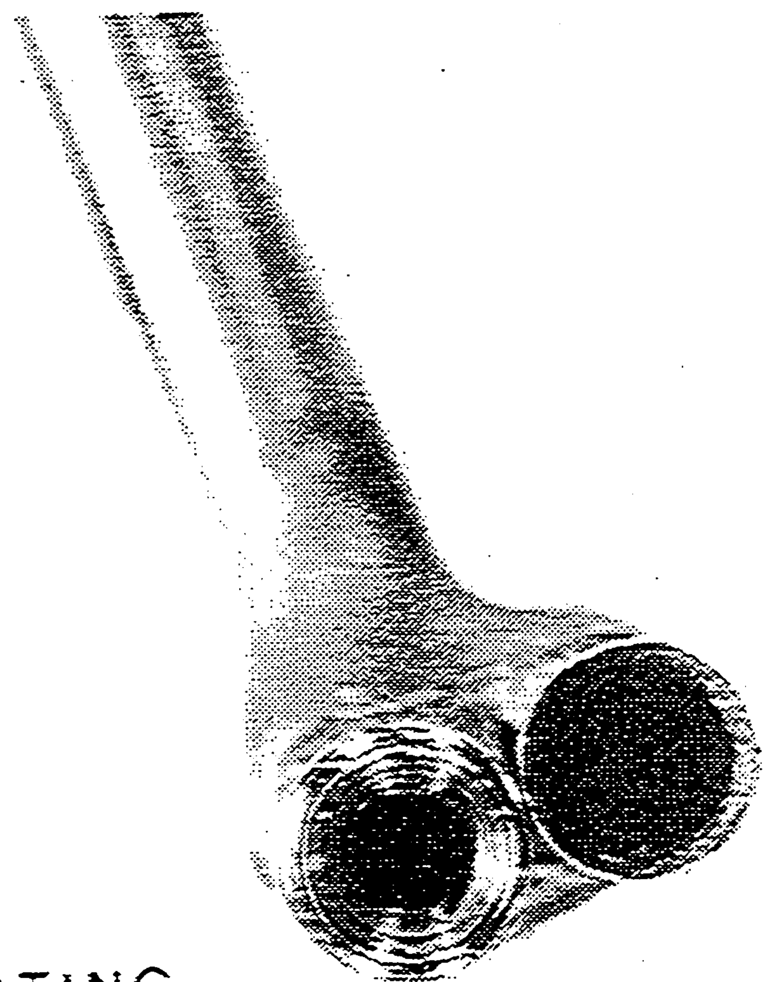


HOT-FILM OUTPUT SIGNALS AND SURFACE FLOW VISUALISATION FROM SUCTION SURFACE OF ROTOR OF A RADIAL INFLOW TURBINE (HUNTSMAN & HODSON, 1993)



The Dual Hot-Wire Aspirating Probe

Alday 1993

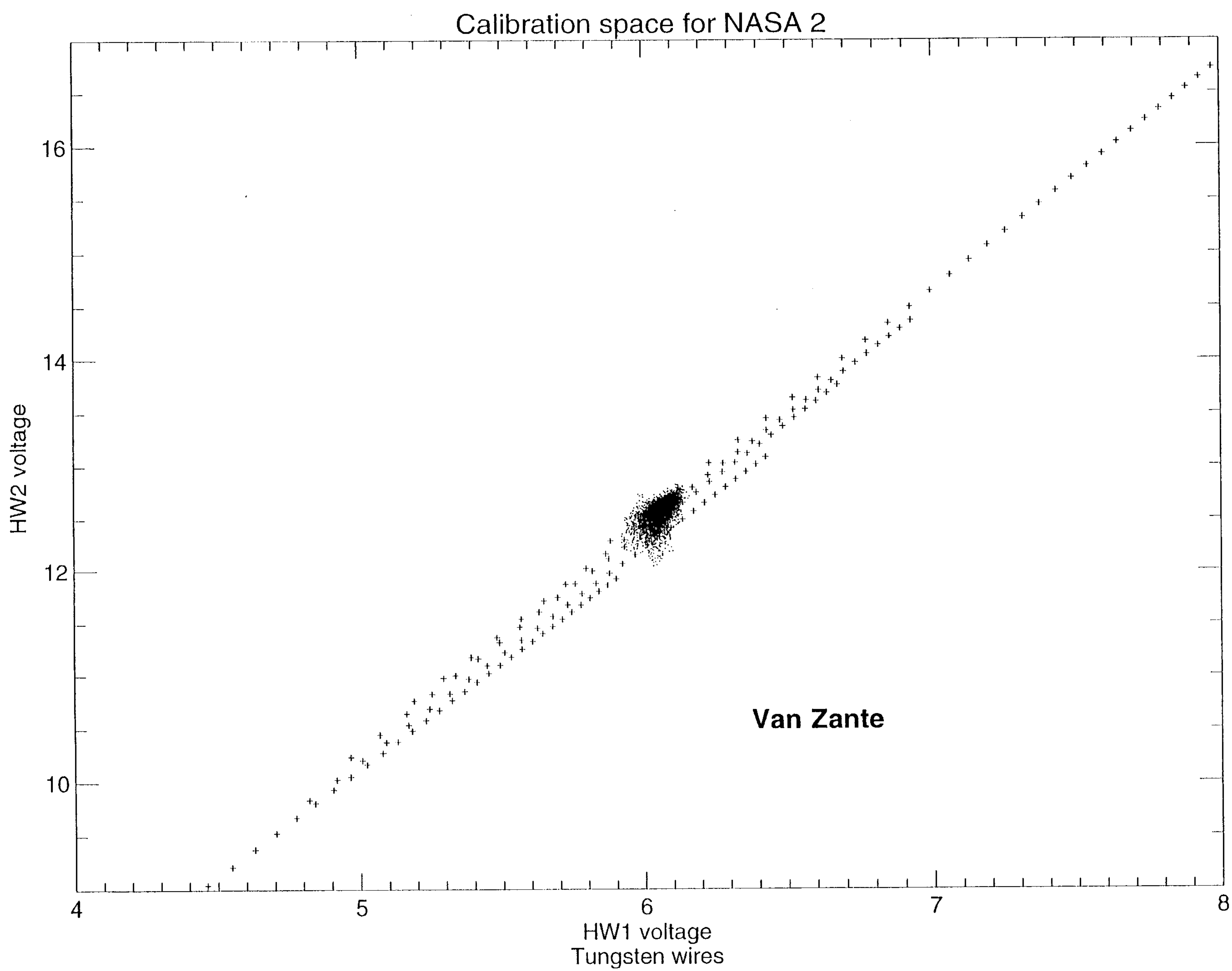


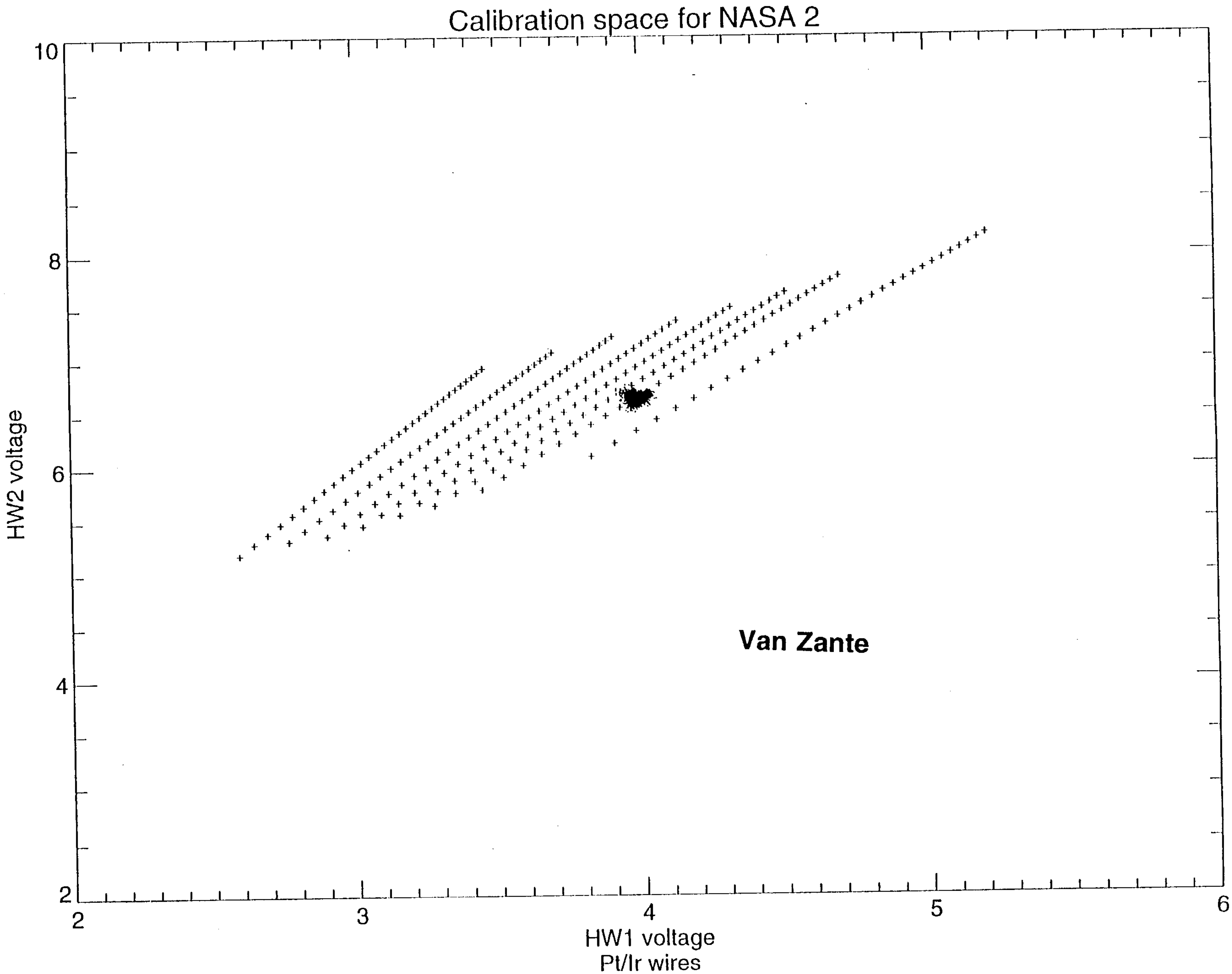
KULITE

ASPIRATING PROBE

FRONT VIEW

Alday 1993


Calibration space for NASA 2
HW2 voltage
16
14
12
10
4
5
6
7
8
HW1 voltage
Tungsten wires
Van Zante


Calibration space for NASA 2
HW2 voltage
10
8
6
4
2
2
3
4
5
6
HW1 voltage
Pt/Ir wires
Van Zante

David C. Wisler

GE Aircraft Engines

WINCAT OBJECTIVES RELATIVE TO THE DESIGN WORLD AND THE REALITIES OF THE 90'S

WINCAT Objectives Relative to the Design World and the Realities of the 90's

David C. Wisler
Mail Stop X409
GE Aircraft Engines
Cincinnati, OH 45215

Introduction

The expressed intention of the WINCAT workshop is to highlight new issues and approaches associated with inherent unsteadiness in turbomachinery. This highlighting will set the stage for a new Air Force Basic Research Initiative in this area. As we make our presentations to this workshop, it was requested that we do not review our past or current work. Instead, we have been asked to discuss the issues and approaches relative to how these new initiatives could be conducted.

To that end I have chosen to examine carefully the WINCAT objectives relative to the enormous pressures and upheavals in the 90's that are re–molding our industry. I then offer for consideration an approach for selecting research topics consistent with these objectives. It is my hope that this candid examination will help focus discussion on relevant issues that I believe should be addressed before new research initiatives are begun.

I recognize that the areas to be examined may be unsettling to some; however, to proceed without such discussion is ingenuous.

WINCAT Objectives

It is well–known that research objectives are varied. One can initiate research with the goal of understanding the phenomenon because it is interesting, or complex, or adds to our enlightenment, etc. These studies tend to be described as *academic* (or basic technology) endeavors, and for simplicity I will use this term in later viewgraphs. One can also initiate research with the goal of immediate applicability or practicality – because the business needs an immediate solution to a problem that is interfering with the safety, performance, sales, profit, etc., of its product. These activities I will describe as *design/critical* technology endeavors. One can then initiate research activities that try to link the two endeavors, and I will call these *enabling* technology endeavors. All three have their legitimate place.

My question is "Where do the WINCAT objectives fit?"

The WINCAT objectives are specific as outlined on Viewgraph 2. Namely,

> "... to start a dedicated effort in pursuing a detailed understanding of unsteady phenomena from both the component and specific phenomeno–logical perspectives...
> ... should lead to the development of a design approach that fully accounts for the various features of unsteadiness...
> ... brings about a major advancement in turbomachinery."

The scope of these WINCAT objectives actually includes elements of all three of the endeavors described above, especially when one talks about "leading to the development of a design approach" and achieving "a major advancement in turbomachinery".

These objectives are ambitious. My concern, seen in Viewgraph 3, is that WINCAT could embark on a singularly *academic* approach often used in the 70's and 80's without recognizing: (1) the current business environment which is driving the industry to fundamental changes and new ways of operating, and (2) the need to understand and address the design and enabling endeavors which are implicit in WINCAT's objectives.

The Changes

Large and significant changes are taking place in our industry. These changes are being driven by economics and by new business attitudes and practices. As seen in Viewgraph 4, the changes are in money, people, type of technology funded, time and attitudes.

The financial losses of the airlines worldwide have been enormous in the past few years. US losses are a staggering $10 billion dollars. These losses total more than the entire profit of the industry since it began. Consequently, commercial engine sales are sharply lower. In the military arena, far fewer orders are on the horizon as a result of the peace dividend after the opening of the Berlin Wall.

This has precipitated a dramatic reduction in employment at GE Aircraft Engines (GEAE) and in other engine companies in the US. Employment at GEAE worldwide has fallen to about 52% of what it was in the late eighties (from 42,000 people to 22,000). At GE Cincinnati, it has dropped to about 40% of what it was (20,000 people to 8,000). The mix of skills is also changing. For example, the number of CFD code developers has been dramatically reduced in some areas to a level of 20% of what it used to be.

The type of technology being funded is changing also. Money to support enabling technology has been reduced to nearly zero. The money for critical technology (the stuff you must do to sell your product or fix a field problem) has been reduced. There is no more "technology for technology's sake". Funding for projects is being given careful scrutiny.

The time available to do things has been greatly reduced. For example, the time from "Concept Go–Ahead to Certification" has been reduced to 36 months, and that includes 24 months to procure hardware and test. As you can see, this means that the time available for design is reduced, forcing designers to be more creative and to re–think 'what is really necessary to be done'.

Attitudes have also changed in response to these technical and market realities. Quotes in Viewgraph 5 from our top executives express the gravity of the situation. Market realities have forced us to look at how technology interacts with the cost of doing business, as simplistically stated in Viewgraph 6. In days of yore, we computed selling price by adding together the manufacturing cost and the profit. If one or both of these goes up, you raise the selling price. Today, a new inverted equation emerges as selling price is being driven down by fierce competition while profit wants to be held or increased. Obviously the manufacturing cost must come now down. This, coupled with a much lower sales volume, has resulted in virtually eliminating enabling technology, reducing critical technology, reducing design costs, and significantly reducing the number of employees.

The fundamental change in thinking is expressed in Viewgraph 7. Two decades ago we were viewed as a technology–driven growing industry. Today, our top executives are viewing us as a cost–driven mature (or nearly so) industry, especially in the commercial arena. Don't misunderstand. We are still a high–technology industry. Technology is important, but these changes have affected the amount and mix of money and people allocated to advancing technology. How much more and what kind of technology do we really need?

This whole situation was marvelously expressed by an add appearing in the Wall Street Journal in which an orchestra conductor was standing up in front of his orchestra scratching his head. Half of the players were missing. The chairs and instruments were still there, but the people to play them were gone. The caption read, "How are we going to conduct business now?"(Viewgraph 8).

The New Working and Research Environment

The question is not rhetorical. How are we going to conduct turbomachinery research and design in this new environment? And what does all of this have to do with WINCAT anyway?

If the WINCAT research objectives are truly meant to be only and purely *academic* endeavors, then one can answer the question easily – The same way we did before. The new environment means little. In fact one can omit this whole presentation, although I would then suggest that the objectives be modified to remove reference to design approaches and major advancements. Such a program is not without merit.

However if the objectives are to stand as written, then I think that a careful assessment of enabling and design endeavors in the new environment is important. The current situation is real and serious. Some have suggested that this is just a downturn like all of the others. Don't get disturbed, it's happened before. In a year or so, this too shall pass and things will be back to the way they were with business going on as before. Perhaps, but I don't think so.

I do believe things will turn around. But that's not the point. The point is that people who say such things do not understand the effect that this huge upheaval is having. They do not understand the absolute resolve of GE's CEO (1) to change fundamentally our attitudes about the way GE does business, (2) to assure that our business remains strong and properly downsized and (3) to assure that we do not go back to old ways of doing things when business picks up.

The Technologist and the Designer

If WINCAT, with limited funds, is to achieve its stated objectives, I think it needs to select research topics with a view toward understanding what designers need and how that differs from what technologists would do. Projects can still have a research nature, but the usefulness and potential payoff of the research must be considered. Within the new environment, the cost of implementing the research into the product must also be weighed – and this is receiving great scrutiny.

To open the discussion, I suggest that we look at the differences between typical technologists and designers, as outlined in Viewgraph 9. This difference has been exasperated by the new working environment.

Technologists generally strive for a more–detailed understanding of phenomena. They revel in the fully 3–D, unsteady Navier Stokes or Euler CFD solutions, the detailed experiment on unsteady interaction of airfoil wakes with boundary layers, active control, and lest–we–forget turbulence in all of its manifestations. In other words they usually deal with the more–*academic* endeavors. It's exciting and people love it.

Engineers on the other hand, strive to make the complex more manageable so that they can design things. Yes, they use the 3–D viscous, steady codes, etc. in design work. This is important where needed. But they strive to reduce the unsteady fully 3–D to the steady, circumferential average. They look for more–simplified or empirical approaches. Simplicity and speed are important. People love this too. It's not anti–technology, but rather selective technology

I'll suggest, as Viewgraph 9 depicts, that technologists generally push toward a WINCAT approach to design in which a full accounting–for or detailed understanding of features is sought, while engineers push toward an industry approach of working around things that are not (and don't necessarily need to be) fully understood to achieve a good design. As I stated earlier, this difference is exasperated by the new working environment in which there are far fewer engineers to run the great number of CFD codes and analyze the meaning of the results.

I do not want the above generalizations to be carried too far. Certainly there are technologists who strive very hard to make the complex more manageable and who take a mass of seemingly structureless data and provide a unified way of understanding it. This in my view is the goal. The giants in our field, Prandtl, G.I. Taylor and Von Karman, are prime examples of technologist who have done this. However, many technologists are mired in the pathology of the minutia.

I read recently an article in Invention and Technology (Winter '93) entitled "How Engineers Lose Touch." The following statement from this article struck me. "Despite the enormous effort and money that have been poured into creating analytical tools to add rigor and precision to the design of complex systems, a paradox remains. There has been a harrowing succession of flawed designs with fatal results – the Challenger, the Stark, the Aegis system in the Vincennes, and so on. ... Bad design results from errors of engineering judgement which is not reducible to science or mathematics" (Viewgraph 10).

This leads me to Viewgraph 11 which shows what I'll propose is a myth; namely, that "A detailed understanding of and a full accounting for all features of a complex flow *necessarily* leads to better designs and major advancements." I propose this not to step on sacred toes but rather to bring a sense of realism into the picture. Please do not misunderstand the statement, because understanding and accounting for complex features of flows is important to the design process. Technology is important. However one could infer from the WINCAT objectives that if we just had this detailed understanding of unsteady flow and if we fully accounted for all unsteady things in our newly–developed design system, then we would produce a better design and have major advancement.

What is omitted here is that designers are very clever people who, with experience and sensible judgement, are able to engineer their way around things they don't understand. There are numerous examples in our current technology where a subsequent better or more–detailed understanding (or computer solution) of the flowfield has not led to a better design. That's why we must understand the basic differences between the designer and the technologist, as illustrated in Viewgraph 9.

Here is a case in point. Compressor polytropic efficiency is 92% or higher. How will a very detailed understanding of the wake/boundary layer *unsteady* interaction bring about a major advancement in efficiency? We've been doing sensible, empirical and computer parametric studies on airfoil shapes for years to optimize things. We've been very successful. Understanding more unsteadiness details may not help us improve designs.

A Suggested Approach

How should we as a workshop begin to sort out what advice we should offer WINCAT in light of the realities of reduced funding, large lay–offs, and changing attitudes in the 90's? Remember, to achieve the stated objectives, WINCAT results must ultimately lead to teaching engineers how to bend the metal differently to improve performance.

I'll suggest that instead of just reviewing everyone's current work, which can lead to random discussion, we should apply the first rule scuba divers are taught to use when problems arise. That

is Stop, Breathe, Think and then Act.

In my view we must first STOP and ask some soul–searching *questions* as shown in Viewgraph 12. We must make sure that we formulate and address the right questions.

What should we study and why?
How will projects be selected to maximize potential for integration into a design approach?
Who will decide what problems will be studied?
How "detailed" of a detailed understanding are we seeking or do we need?
How "fully" is fully accounts for?
What does "major advancement" mean?
Do the participants understand design?
How will industry participate?

I next suggest that we THINK in terms of evaluating potential topics in a manner shown in Viewgraphs 13 and 14, which I have entitled "On a Scale from One to Ten". These are meant to be food–for–thought, not absolutes. They are first cuts at sorting through issues and trying to find potentially relevant unsteady topics in the current environment described previously. They are meant to open discussion, whereby the audience adds a topic and suggests alternate scores.

The viewgraphs are constructed to show (1) the unsteady phenomenon on the left, (2) the things this phenomenon could affect in the middle, and then on the right, (3) the rating of importance/interest/usefulness as evaluated by the academic, the enabler and the designer respectively. The emphasis must remain on the *unsteady* effects and not on their steady–state approximation.

The Viewgraphs should be read in the following manner. The first point in Viewgraph 13 states: The effects of *unsteady* .... wakes .... ON ... Forced response of airfoils ... has high academic, enabling and design interests of 10. That is, academics find it of high research interest. Those who work in applied research to transfer technology to the design arena find it very relevant. Designers consider it vital to the product. The "P" in the design column means that designers think this topic has high payoff. It would be a winner for WINCAT.

Please note that I am not suggesting that designers drive this whole process. I am suggesting that their input be given serious consideration. Although a designer may personally find a topic interesting in itself, Viewgraphs 13 and 14 are trying to show what the designer would actually use or need in the design process.

Here are the ways that I think such evaluations can be useful. One can

1) Discover research topics that designers think have high eventual payoff. This can spawn academic interest if it does not already exist, which can lead to a WINCAT topic of unsteady flow research. These charts show that forced response, acoustics, and distortion clearly fall into that category. If any topic is of high interest to all three parties, it is a win, win, win situation for WINCAT.

2) Identify topics that are viewed by designers and enablers as having little practical payoff. WINCAT, with limited funding, can choose not to fund these.

3) Identify the in–between topics for which there is little or no design interest, but high academic interest and, in the recent past, moderate enabling interest. For exam–

ple, active control of stall/surge falls into this category at GEAE. Designers of compressors for commercial engines do not want it on the engine at this time (other companies may have differing views). However the topic has high academic interest. Enabling researchers did some work on it in the recent past, and there could be some merit for application if certain problems could be worked out. WINCAT could choose to fund this based on such an assessment.

4) Identify items of important enabling technology where major cuts in funding by industry have been made. WINCAT could address this, not by funding industry, but by funding university graduate students to do their thesis work in industry labs under the joint direction of the university professor and the industry researcher. In this way WINCAT could feel the pulse of designers.

Summary – I'm Optimistic

As Viewgraph 15 states, ours is a very exciting and technical business that will come back, but look for fundamental cultural changes.

Some unsteady flows, such as forced response from wakes, acoustics, stall and surge, hot–spots, to name a few, are clearly of vital importance to turbomachinery and are currently being funded. Other areas, although very stimulating academically, have much less potential to effect performance in a major way. Except for those areas currently being funded/studied, it is not clear to this researcher that a major new campaign to understand more of the details of unsteady flows will produce the kind of major advancements which are envisioned.

If, in this environment, WINCAT intends ultimately to influence the design process in industry by launching research programs in unsteady flow, it must ask the right questions and choose topics relevant to design, i.e. topics whose better–understanding will ultimately teach designers how to bend the metal differently.

WINCAT Objectives

Relative to

the Design World and Realities of the 90's

WINCAT Objectives

... Start a dedicated effort in pursuing a detailed understanding of complex unsteady phenomena that

Leads to

development of a design approach that fully accounts for various features of unsteadiness

Brings about a major advancement in turbomachinery

–2–

Concern

WINCAT may embark on an academic approach

used in the 70's and 80's without recognizing

1) the fundamental business changes
2) the design and enabling processes

and therefore be less–effective.

–3–

The Changes

1989		1993
	Airline Losses (Worldwide)	\$18 B
	Airline Losses (US)	\$10 B
42,000	GEAE Worldwide	22,000 (52%)
20,000	GEAE Cincinnati	8,000 (40%)
A	CFD Code Developers	(<20% of A)
\$ M's	Enabling Technology	0
\$ M's	Critical Technology	Reduced

No more Technology for Technology's sake

Open	Concept Go–Ahead to Certification	36 mo.

–4–

Market Realities

"... driving us to change *fundamentally* the way we do business"

"Business as usual is a strategy for disaster"

"We just can't hunker down, wait for better times and expect to survive"

"The glory days of the roaring 80's are gone!"

"We will size the business to the market"

–5–

Market Realities

Before:

Manufacturing Cost ↑ + Profit ↑ = Selling Price ↑

Now:

Selling Price ↓ – Profit ↑ = Manufacturing Cost ↓

Technology + Design + # Employees ⇩ + Mat'l ⇩ + Prod. + ...

Develop. Cost ⇩

~~Enabling~~

Critical ⇩

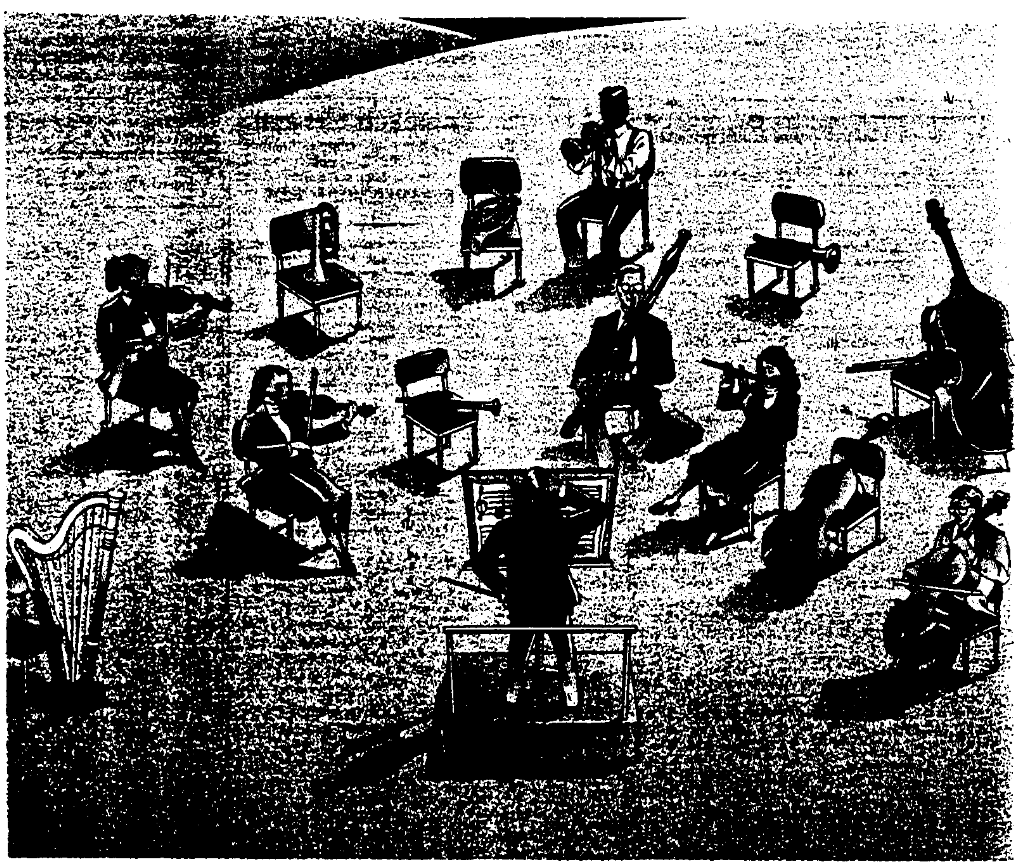
–6–

Fundamental Change

Before:
Technology–Driven Growing Industry

Now viewed as:
Cost–Driven Mature (or nearly so) Industry

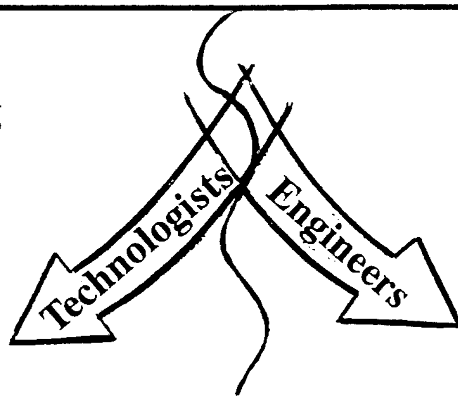
–7–



How are you going to conduct business now?

Detailed Understanding

Simplicity, Speed



WINCAT

Industry, Airlines

3−D Unsteady NS/Viscous Euler ➧ ➧ **Circum. Avg. Steady**

BL,Wakes, Stg Interact ➧➧ **Simplified, Empirical**

Active Control of Stall ➧ **Passive Control** ➧ ➧ **Keep Off Engine**

Bad designs result from errors of engineering judgement which is not reducible to science and mathematics.

MYTH

A Detailed Understanding of and a Full Accounting for

all Features of a Complex Flow Necessarily Lead to

1) Better Designs

2) Major Advancements

–11–

?? Questions ??

What should be studied and why?
Who will decide what problems will be studied?
Who will conduct the research?

How "detailed" is detailed understanding?
How "fully" is fully accounts for?
What does "major advancement" mean?

Do the participants understand design?
How will industry participate?
How will the design approach be developed?

–12–

On a Scale of 1 to 10

Effects of Unsteady	On	Interest Academic	Interest Enabling	Interest Design
Wakes	......Forced Response of Airfoils	10	10	10P
	......Downstream Boundary Layers	7	3	1
	......Location of Transition	8	5	2
	......Recovery of Wake Defect	3	1	1
	......Noise	8	8	8P
	......Hot Spots	?	8	8P
Boundary	......Forced Response		?	
Layers	......Loss	?		1

Effects of Unsteady	On	Interest Academic	Interest Enabling	Interest Design
Distortion	......Forced Response	10	10	10P
	......Aero Performance	5	8	10P
	......Stall Margin	6	9	10P
	......Transfer through Cavities	2	5	7P
Clearance	......Aero Performance	3	8	9P
Cavity	......Aero Performance	2	4	7P
Turbulence.....		9	3	3
Active Cnt'l...	Stall/Surge Margin	9	4	2
Passive "	......Stall/Surge Margin	4	5	8

I'm Optimistic

It's an Exciting Business, (still very technical)

It WILL Come Back.......BUT,

It Will Be Fundamentally Different (with fundamental cultural and business changes)

If WINCAT objectives are to influence the design process in industry, then topics for study must be chosen carefully and in light of the realities of our business in the 90's.

Workshop on Inherent Unsteadiness in Compressors and Turbines
October 4-6, 1993 Purdue University

Some Unsteady Effects on Two-Dimensional and Three-Dimensional Separations

by
Roger L. Simpson
Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

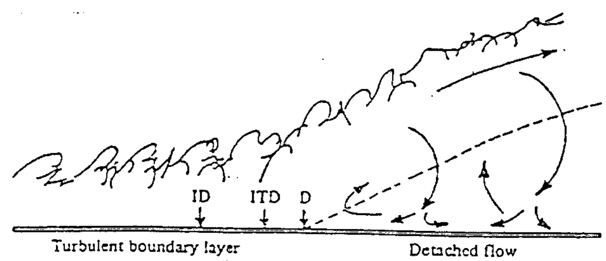
1. **NATURE OF 2-D UNSTEADY SEPARATIONS FROM STREAMLINED SURFACES WITH FREE-STREAM UNSTEADINESS**

2. **SELF-INDUCED UNSTEADINESS AT THE NOSE OF A BLADE/HUB JUNCTION**

FIGURE 1. Sideview schematic diagram of the test section with the steady free-stream separating turbulent boundary layer (Simpson *et al.* 1981*a*) on the bottom wall. The major divisions on the scales are 10 in. Note the baffle plate upstream from the blunt leading edge on the bottom test wall and side- and upper-wall jet boundary-layer controls.

FIGURE 2

INSTANTANEOUS BACKFLOW BEHAVIOUR STRUCTURE AND NATURE OF BACKFLOW IMPORTANT FOR PROPER MODELING.



A FLOW MODEL WITH THE COHERENT STRUCTURES SUPPLYING THE SMALL MEAN BACKFLOW. ID DENOTES INCIPIENT DETACHMENT; ITD DENOTES INTERMITTENT TRANSITORY DETACHMENT; D DENOTES DETACHMENT. THE DASHED LINE DENOTES $\bar{U} = 0$ LOCATIONS. FROM SIMPSON ET AL. (1981B).

1. LARGE EDDIES GROW DURING DETACHMENT
2. LARGE EDDIES SUPPLY TURBULENCE ENERGY TO BACKFLOW AND CONTROL OUTER REGION ENTRAINMENT RATE.
3. LARGE EDDY BEHAVIOR SCALES ON MAXIMUM SHEAR STRESS.
4. DIFFUSION AND DISSIPATION OF TURBULENCE ENERGY IN BACKFLOW.
5. SMALL $-\overline{uv}$ IN BACKFLOW; COLES "LAW-OF-THE-WALL" DOES NOT APPLY.

FIGURE 3

LAW OF THE BACKFLOW (SIMPSON, 1983) HOLDS FOR LOW BACKFLOW VELOCITIES,STEADY AND UNSTEADY FLOW; LOW TURBULENCE ENERGY PRODUCTION NEAR WALL. (Agarwal & Simpson, AIAA J., 1990)

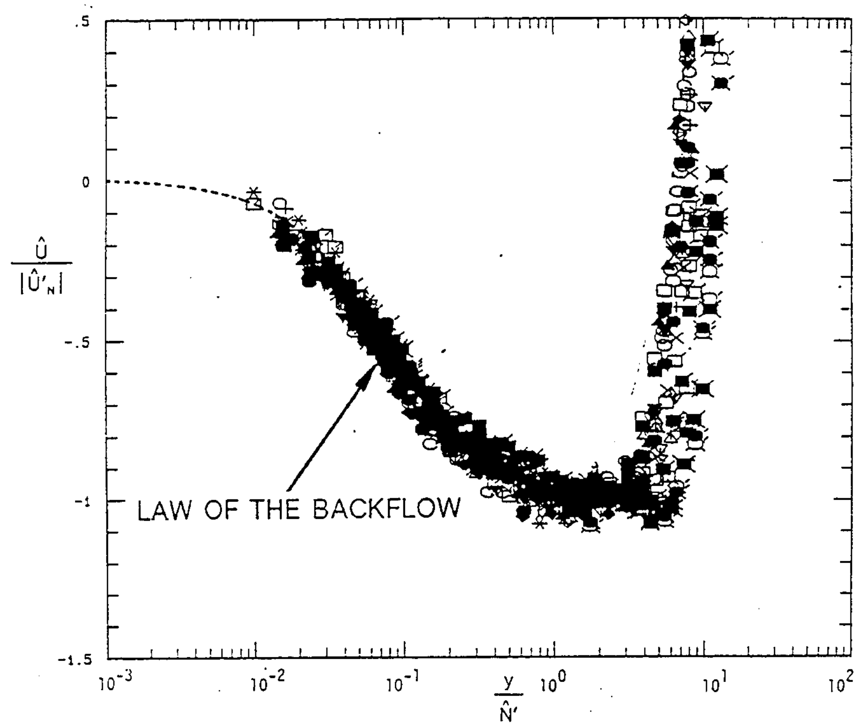
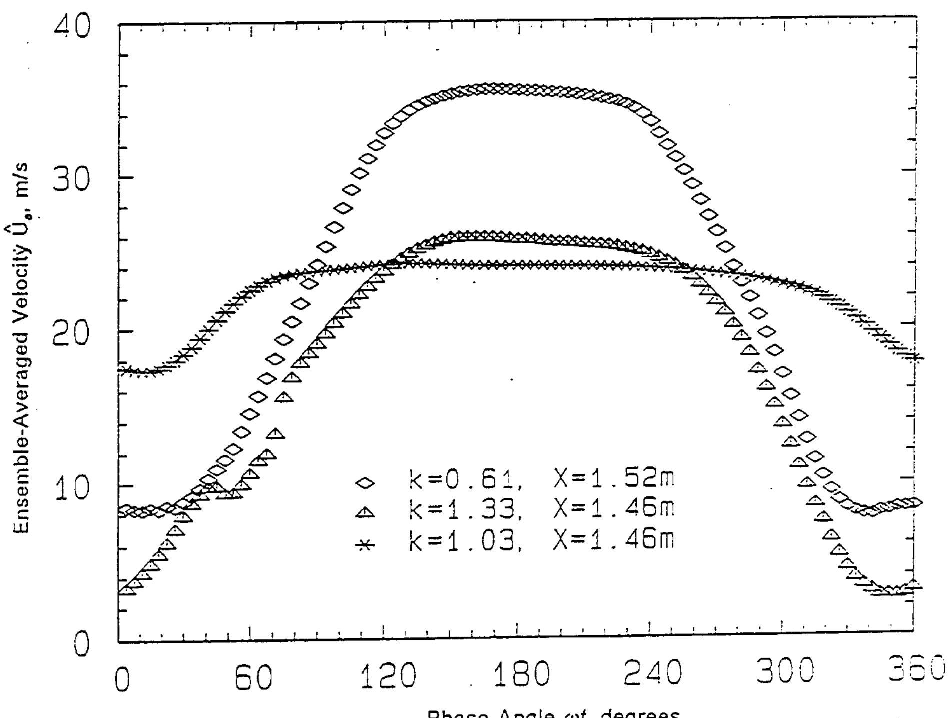


FIGURE 4



Agarwal, Simpson, Shivaprasad, 1992, J. Prop. & Power

Ensembled-averaged free-stream velocity, $\hat{U}_e$ distributions.

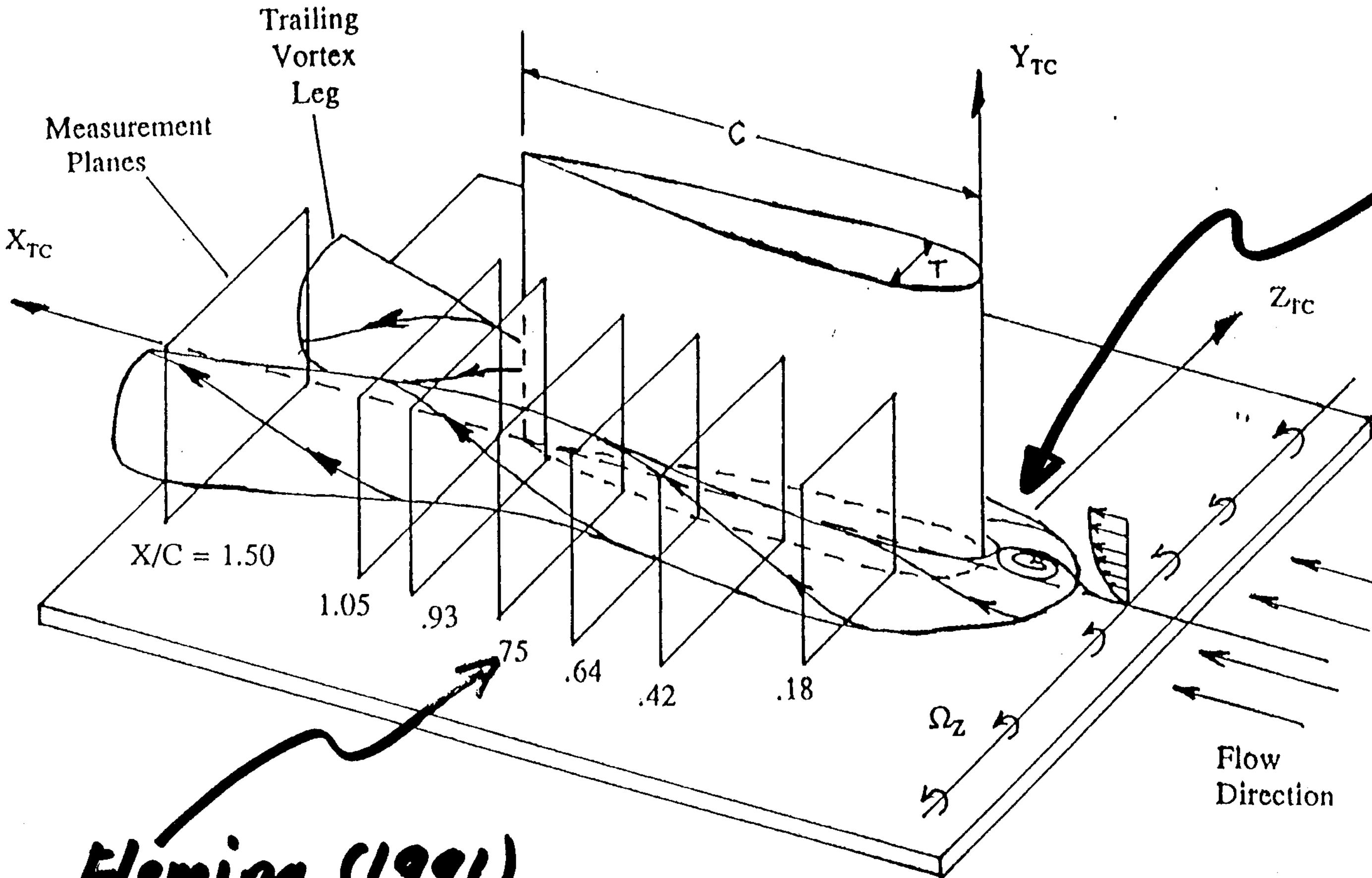
SOME EFFECTS OF UNSTEADINESS ON T.B.L.

1. Low amplitude attached flows - no measurabl effect on mean flow or turbulence structure at practical reduced frequencie:

2. Large amplitude ($\tilde{u}/\bar{u} \sim 1/2$ to $3/4$) - nonlinear effects important: flow reverse in nozzles; unsteadiness <u>waveform</u> strongly influences stall zone;

3. Large effects for unsteady separated flows: greater pressure recovery than steady flow with same mean free-stream velocity.

Idealized wing-body junction flow experiment



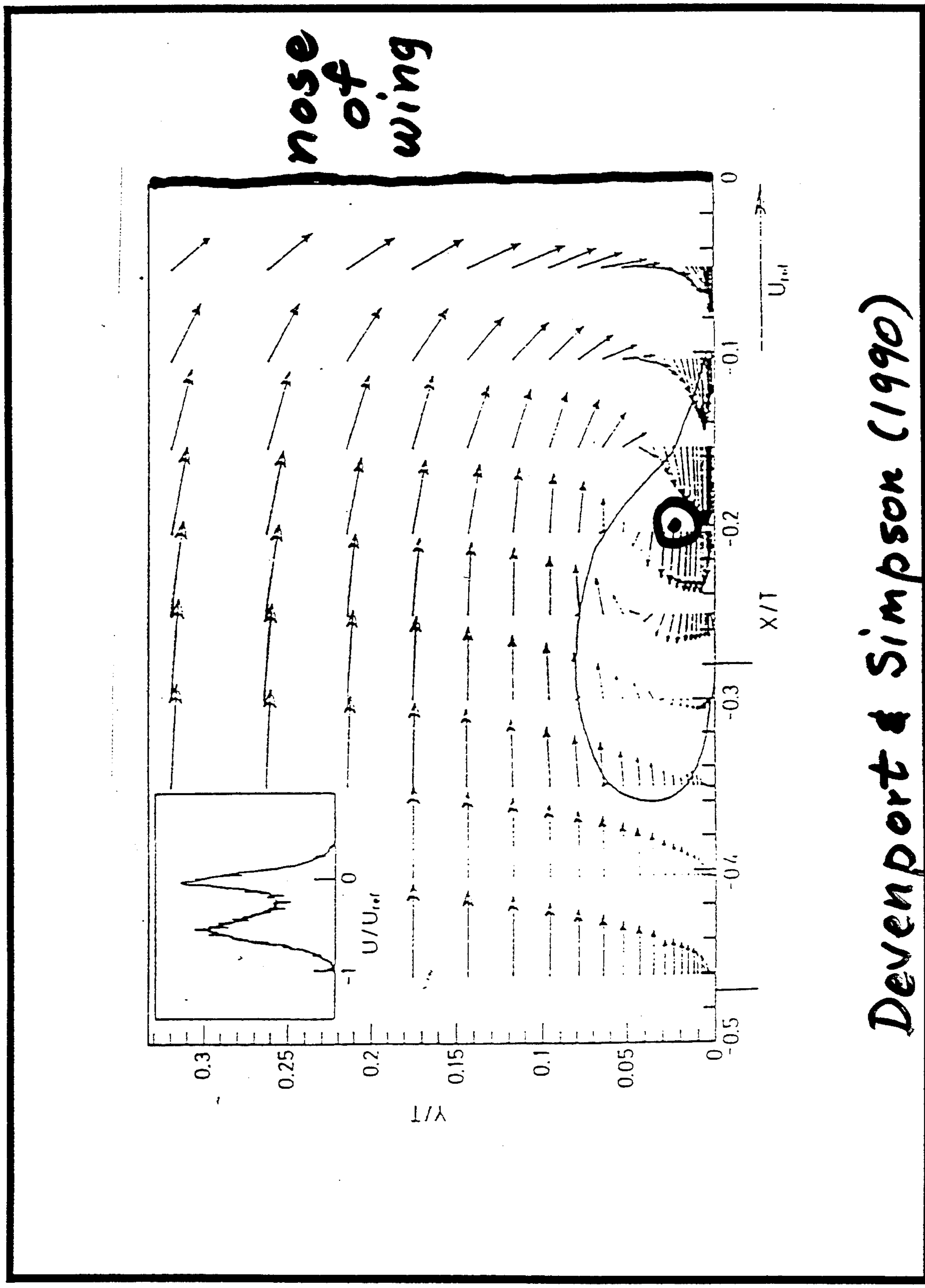
Fleming (1991)
Devenport & Simpson (1990)

Devenport & Simpson (1990)

Kim (1991)

Rife (1991) (p' v')

Shinpaugh (1993) scanning LDV


nose of wing
Devenport & Simpson (1990)
Y/T
X/T
U/U_ref
U_ref
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.5
-0.4
-0.3
-0.2
-0.1
-1

VPI&SU

Kim (1991)

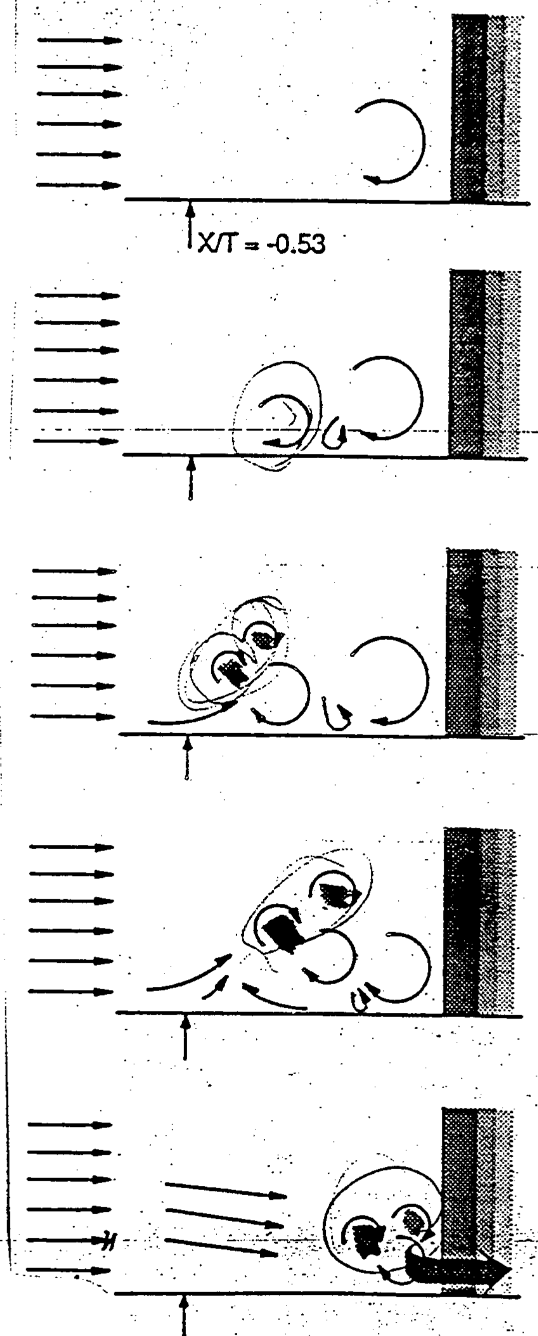


Figure 62. Descriptive model for the sequence of flow events in the nose region of a wing–body junction

SUMMARY: BIMODAL UNSTEADY WING/BODY JUNCTION FLOW

- present when wing sufficiently "blunt" (Ölçmen)
- when present, bimodal in velocity and surface press. fluctuations (Ölçmen; Rife)
- bimodal unsteadiness appears to be Markovian process. (Tropea)
- inviscid vortex stretching rate is a strong function of "bluntness" (Fleming, 1991)
- H_2 bubble videos show vortex structure. (Kim, S.A., 1991)
- Not strong Reynolds number dependence. ($330 < Re_\theta < 7000$).

WING/BODY JUNCTION FLOW

Devenport, W.J. and Simpson, R.L. (1990) "Time-Dependent and Time-Averaged Turbulence Structure Near the Nose of a Wing-Body Junction," J. Fluid Mech. 210, pp. 23-55, 1990.

Ölçmen, S.M. (1990) "Study of a Three-Dimensional Turbulent Boundary Layer," VPI-AOE-178.

Devenport, W.J. and Simpson, R.L. (1992) "The Flow Past a Wing-Body Junction - An Experimental Evaluation of Turbulence Models," AIAA Journal, Vol. 30, pp.873-881.

Ölçmen, S.M. and Simpson, R.L. (1991) "An Evaluation of Some Turbulence Models from a Three-Dimensional Turbulent Boundary Layer Around a Wing-Body Junction," Paper 9-4, 8th Symposium on Turbulent Shear Flows, Sept. 9-11, Munich, Germany.

Kim, S.A., Walker, D.A.,and Simpson, R.L. (1991) "Observation and Measurements of Flow Structures in the Stagnation Region of a Wing-Body Junction," VPI-E-91-20, DTIC distribution).

Fleming, J.L., Simpson, R.L., and Devenport, W.J. (1992) "An Experimental Study of a Turbulent Wing-Body Junction Flow," AIAA-92-0434, AIAA 30th Aerospace Sciences Meeting, Jan. 6-9, Reno, NV; in press, Exp. in Fluids.

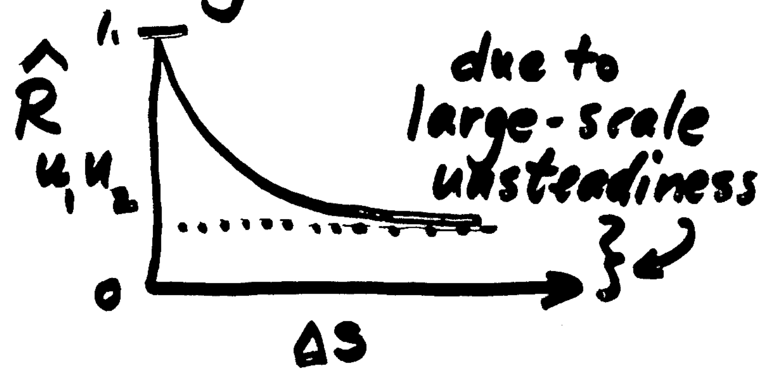
Ölçmen, S.M. and Simpson, R.L. (1992) "Influence of Wing Shapes on the Surface Pressure Fluctuations of a Wing-Body Junction," AIAA-92-0433, AIAA 30th Aerospace Sciences Meeting, Jan. 6-9, Reno, NV; accepted for AIAA Journal.

Ölçmen, S.M. and Simpson, R.L. (1992) "On the Near Wall Similarity of Three-Dimensional Turbulent Boundary Layers," Journal of Fluids Engineering, TASME, Vol.114, pp.487-495.

Ölçmen, S.M. and Simpson, R.L. (1993) "Evaluation of Algebraic Eddy-Viscosity Models in Three-Dimensional Turbulent Boundary Layer Flows," in press AIAA Journal.

Rife, M.C., Devenport, W.J., and Simpson, R.L. (1992) "An Experimental Study of the Relationship Between Velocity and Pressure Fluctuations in a Wing-Body Junction," VPI-AOE-188, submitted to DTIC.

Length Scales in Turbulent Flow



$$\hat{R}_{u_1 u_2}(\Delta s) = \frac{\int_0^T u_1(t)\, u_2(t)\, dt}{T\left(\overline{u_1^2}\ \overline{u_2^2}\right)^{1/2}}$$

$$\hat{R}_{u_1 u_2}(\Delta s) = \int_{V(\vec{k})} \phi_{12}(\vec{k})\, e^{i\vec{k}\cdot\vec{r}}\, d\vec{k} \qquad k = \frac{2\pi}{\lambda}$$

$$f\lambda = U_c$$

length scales from $\hat{R}_{u_1 u_2}(\Delta s)$ are integrals over all wavenumbers. MUST USE MULTIPLE SENSORS

By examining coherency, can define length scale for each frequency

$$\text{coh.} = \gamma^2 = \frac{G_{12}(f)\, G_{12}^*(f)}{G_{11}(f)\ G_{22}(f)}$$

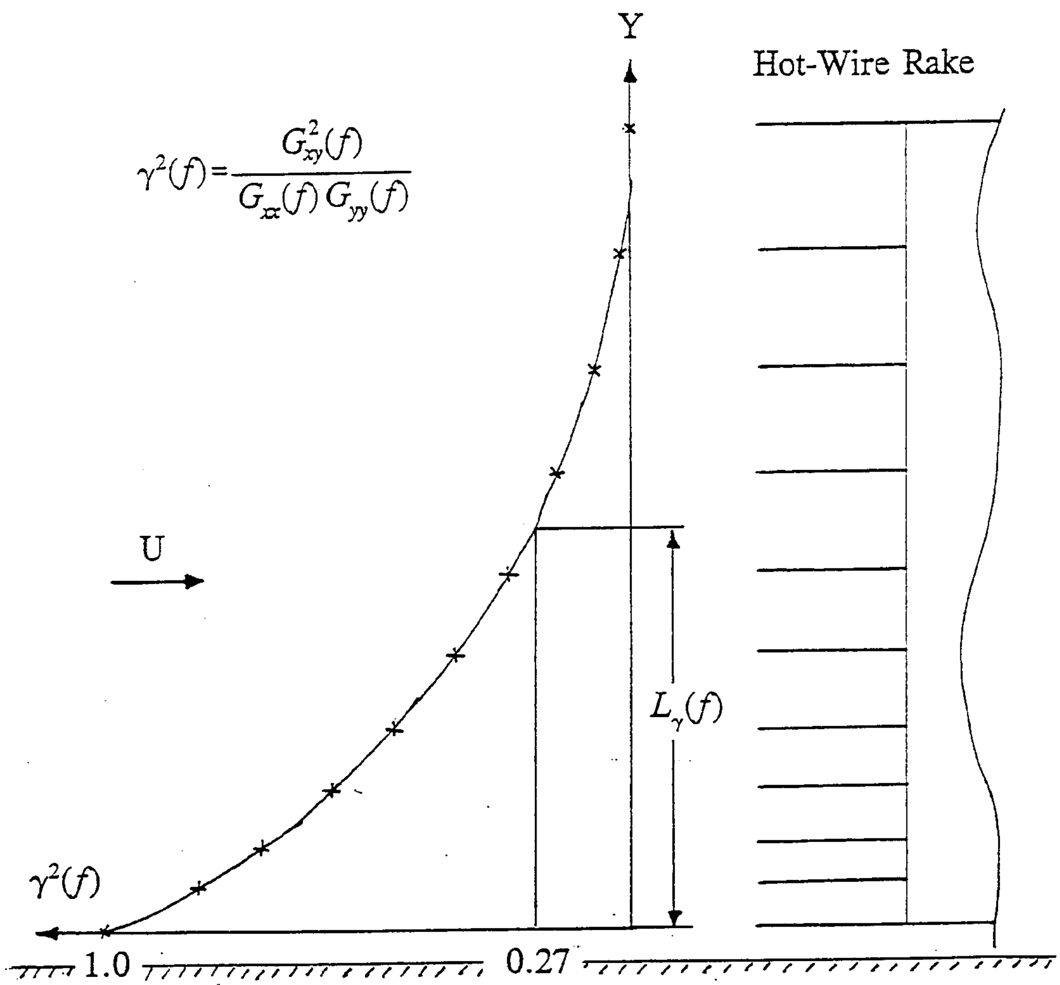


Figure 5(a)

Definition of Coherence Length Scale $L_\gamma(f)$

Nature of Unsteady Signals Can Be Used to Decompose Time-Dependent Data

repetitive waveform

$$\mathcal{U}(t) = \hat{\mathcal{U}}(t) + u_{turb}(t) + u_{jitter}(t)$$

$$\hat{\mathcal{U}}(t) = \overline{\mathcal{U}} + \tilde{\hat{\mathcal{U}}}(t)$$

periodic

$u_{turb}(t)$ and $u_{jitter}(t)$ do not correlate

$u_{jitter}(t)$ may be <u>coherent</u>

$u_{turb}(t)$ has <u>no long time</u> <u>coherency</u>

Using cross-spectral analysis and time-delay correlations, these different contributions can be distinguished.

WINCAT 93

Flow Physics Issues

Michael W. Plesniak

School of Mechanical Engineering
Purdue University

Flow Physics Issues
Turbine Heat Transfer

- **Improvement Potential**
  - current predictions within 20-100%
- **Impact Reliability**
  - "cost of ownership"
- **Complexities**
  - combustor exit nonuniformities
  - unsteadiness
  - secondary flows
  - curvature
  - turbulence
  - pressure gradient interaction
  - FLOW IS NECESSARILY 3D

Flow = steady + unsteady + turbulent

periodic stochastic

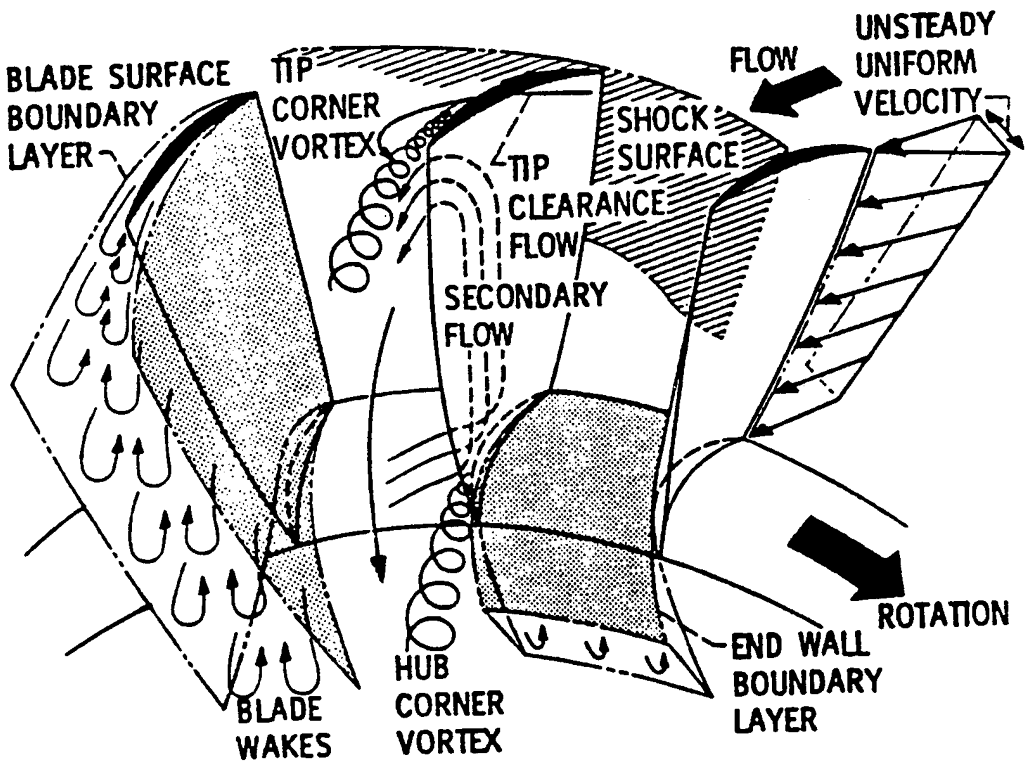


Fig. 1. Compressor blade row flow field characteristics (NASA-Lewis Research Center).

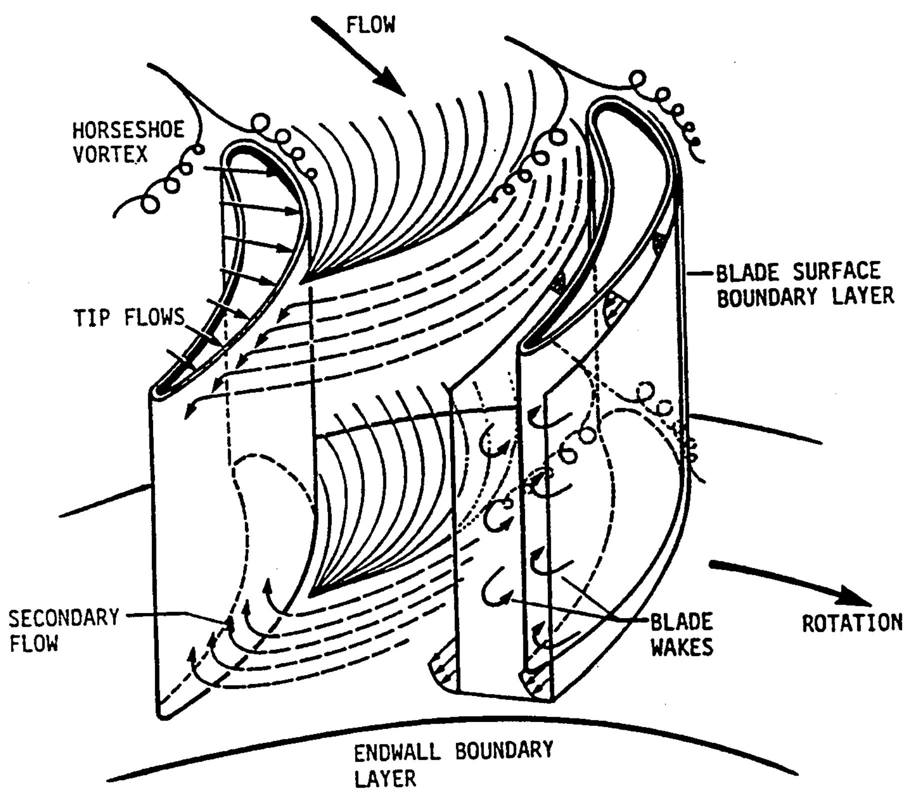
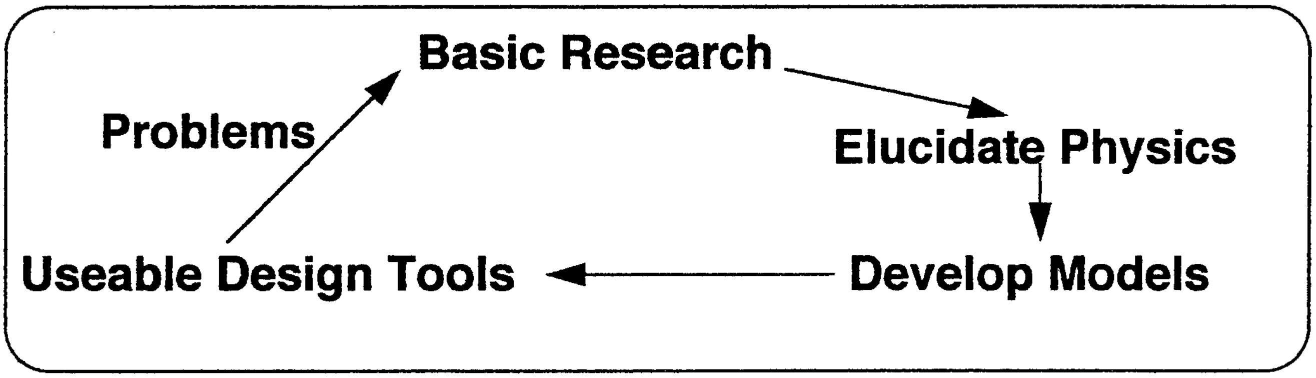


Fig. 2. Turbine blade row flow field characteristics (NASA-Lewis Research Center).

Design of Experiments

- **Levels of Complexity**
  - "clean"- fundamental physics
  - "dirty" - realistic phenomena
- **Need to Link Communities**



- **Borrow Concepts to Interpret Data**
  - coherent structures
  - topology
  - active & inactive motions
  - conditional sampling
  - stochastic estimation
  - wavelet analysis
  - etc.

Current Effort

- Experimental & Analytical
- Slightly Soiled
  - some real effects
  - curvature + axial p-grad
  - 3D
- Steady
- Fundamental Physics
  - momentum transport
  - heat transport
- Interacting Pressure Gradients
  - impact on transport & mixing

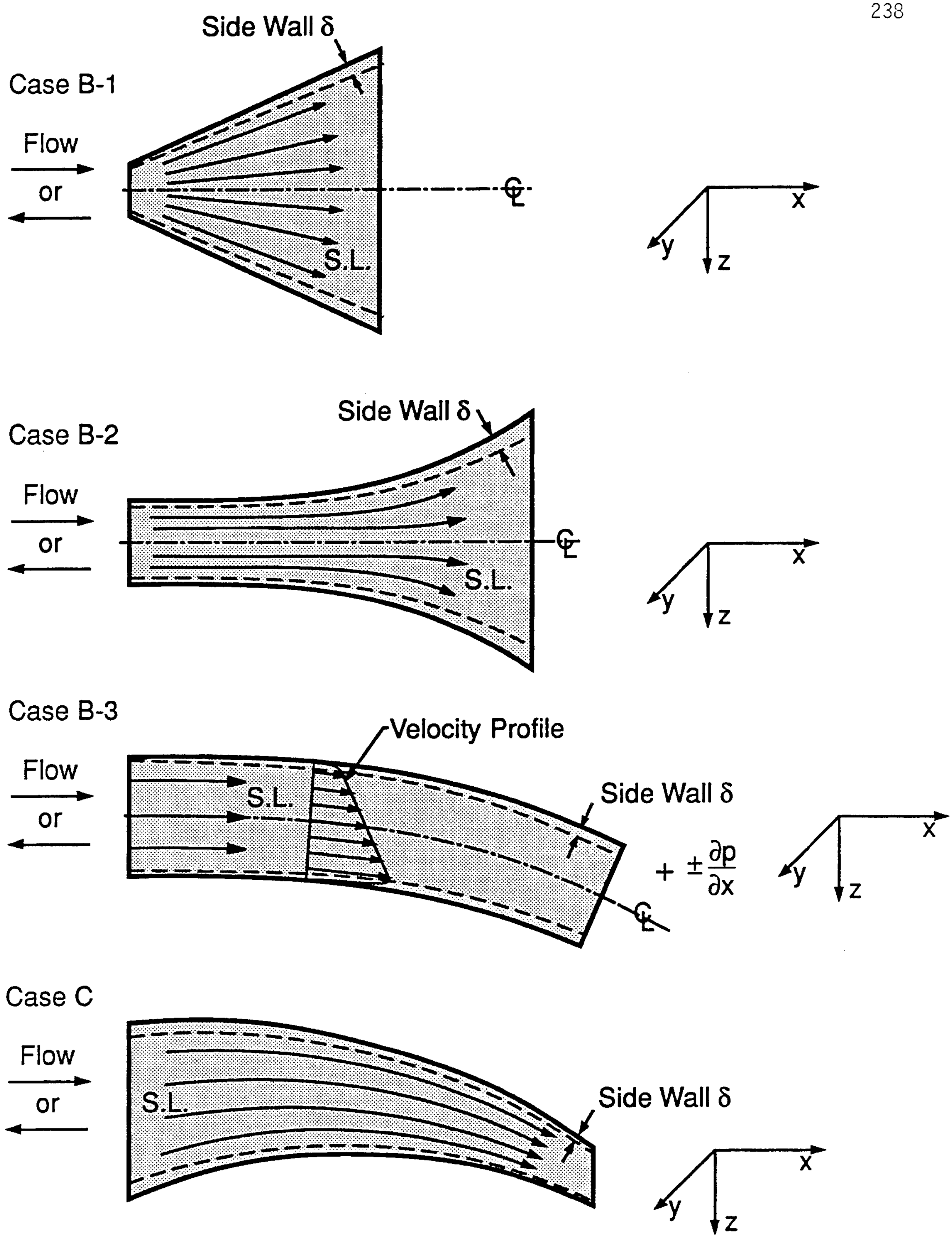


Figure 4. Three-Dimensional TBL Configurations (TBL along Shaded Plate).

Develop Advanced Meas. Techniques

- Field Measurements
  - PIV
  - Pressure/Temp Sensitive Paint
  - Liquid Crystals
  - Interferometry
- Extend to Rotating Machinery
  - get away from point measurements
  - very difficult
- Large Data Sets
  - storage & presentation
  - comparison to CFD
- Use Insight from Physics to Develop Simple Models for Designers

Ernst Eckert

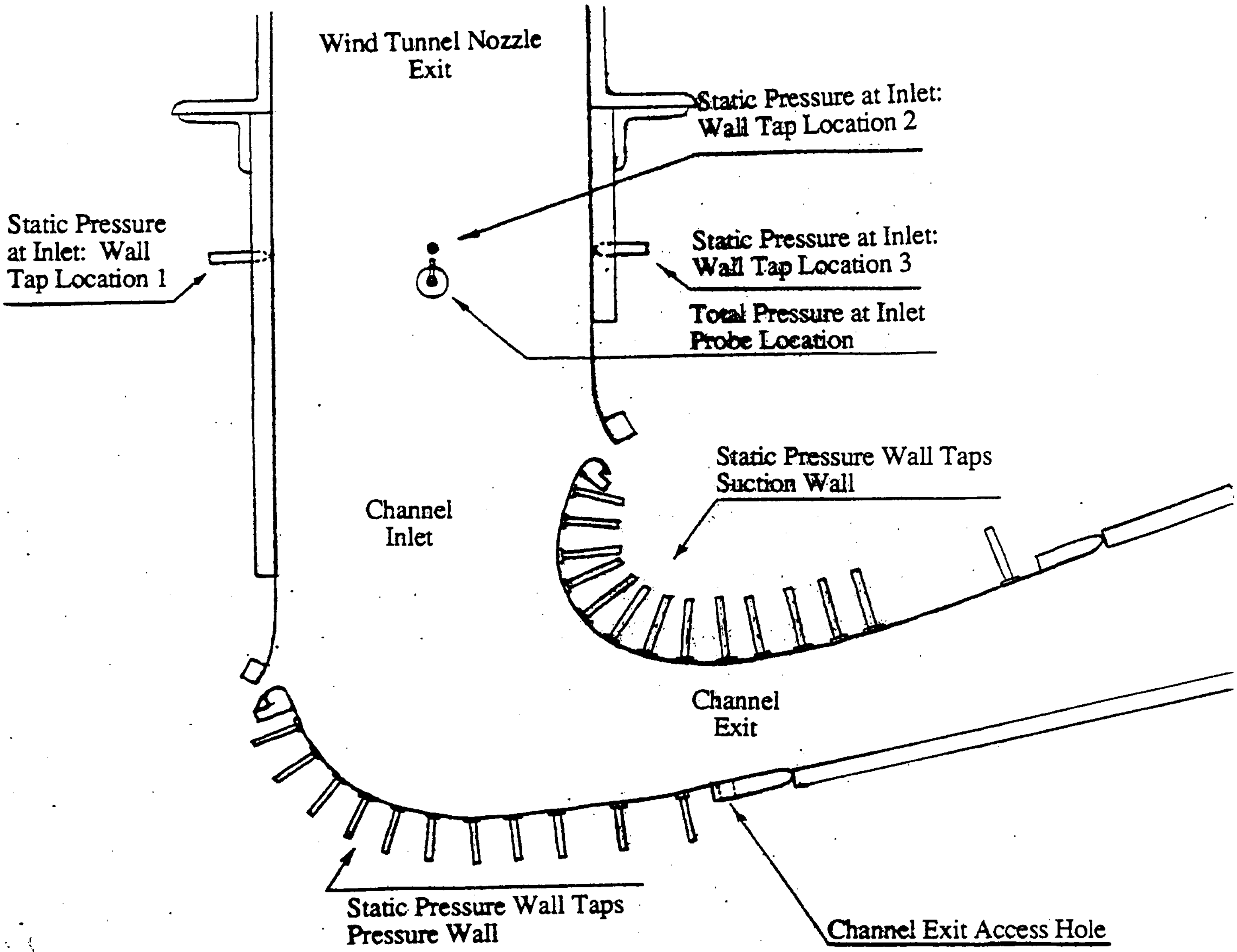
University of Minnesota

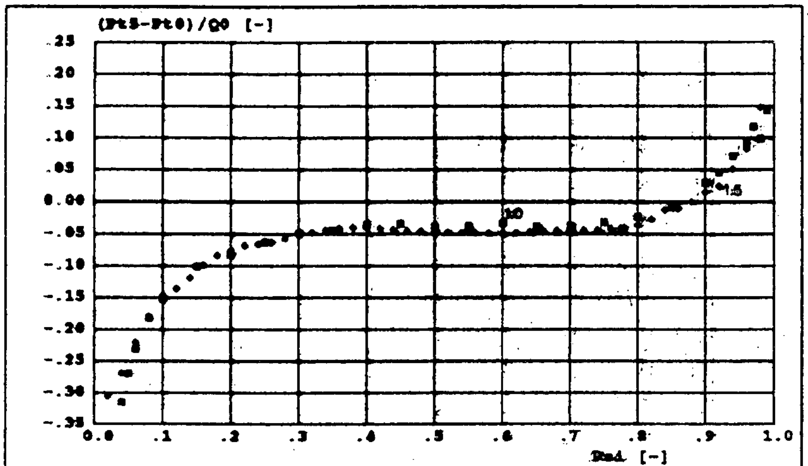
Ernest Eckert

I want to briefly describe a transport process which occurs in unsteady or turbulent flow and which has not yet been mentioned in this workshop. It is called in the literature "cross transport of energy" or "energy separation".

A doctors thesis by K. Heininger at the Federal Institute of Technology studies it in detail for flow through a duct with rectangular cross-section and a side ratio of 1 to 10. Turbulence generators shown in Fig. 1 were installed. They produce turbulence with intensity from 5 to 8.3% and a macro-length scale equal to 0.25 up to 0.5 of the channel width. Downstream of the turbulence generators, the flow moves through a 90 degree bend. The velocity field in the bend was measured in great detail. I will show only time averaged total pressure measurements across the channel upstream and downstream of the bend. In the upper diagram of Fig. 2, the difference in the local downstream pressure minus the upstream total pressure divided by the upstream total minus the upstream static pressure is plotted over the distance between the convex wall (left) and the concave wall (right). The upstream turbulence intensity was 6.8%. It is remarkable that the pressure parameter near the concave wall exceeds the value 1. This means that the total pressure increases in the flow of this region in downstream direction and that energy was fed into it from the neighborhood. The boundary layer there is so thin that it could not be measured. On the other hand, the boundary layer near the convex wall reaches almost to the center of the duct. This cross transport of momentum or energy is explained in the following way: A fluid particle in the bend with certain time average velocity experiences a centrifuged force which is balanced by a radial pressure gradient. An instantaneous velocity higher than the time averaged one is not completely balanced and is thrown outward in radial direction. The opposite occurs to the fluid particle with an instantaneous slower velocity.

The lower diagram in Fig. 2 compares this pressure parameter which was obtained in a baud with a constant cross sectional are with one in which this area increases in the bend so that the cross section at the exit of the bend is 1.5 times the upstream cross section. There is practically no difference between the two curves and it is generally concluded in the thesis from which the figures are taken, that this effect is so strong that it overshadows any upstream differences in the flow. T. Simon and myself study this effect in a channel which simulates the passage between two turbine blades. Figure 3 is a sketch of this channel. The upstream nozzle has a side ratio of 1 to 5. Figure 4 presents the results of total pressure measurements by Dave Smith. The same pressure parameter as before is plotted over a line across the channel. The convex wall is now to the right and the concave wall to the left. The similarity in the shapes of Figs. 2 and 4 is clearly recognizable. The differences existing are probably due to the fact that the flow through the passage in Fig. 3 is strongly accelerated. Accordingly, the measured turbulence intensity in Fig. 4 dropped at the exit cross section in the main stream to 3%. We will continue to study this cross transport and its influence on the boundary layer development and believe that it is of importance for flow in gas turbines.


Wind Tunnel Nozzle Exit
Static Pressure at Inlet: Wall Tap Location 2
Static Pressure at Inlet: Wall Tap Location 1
Static Pressure at Inlet: Wall Tap Location 3
Total Pressure at Inlet Probe Location
Static Pressure Wall Taps Suction Wall
Channel Inlet
Channel Exit
Static Pressure Wall Taps Pressure Wall
Channel Exit Access Hole

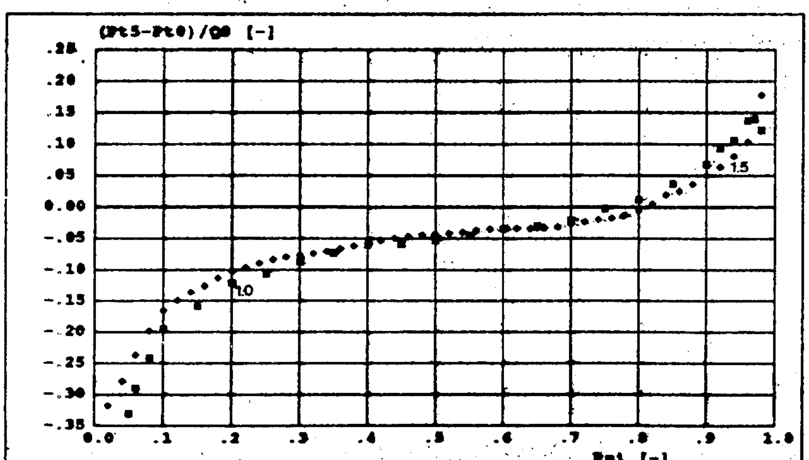


Totaldruckdifferenz Austritt - Eintritt

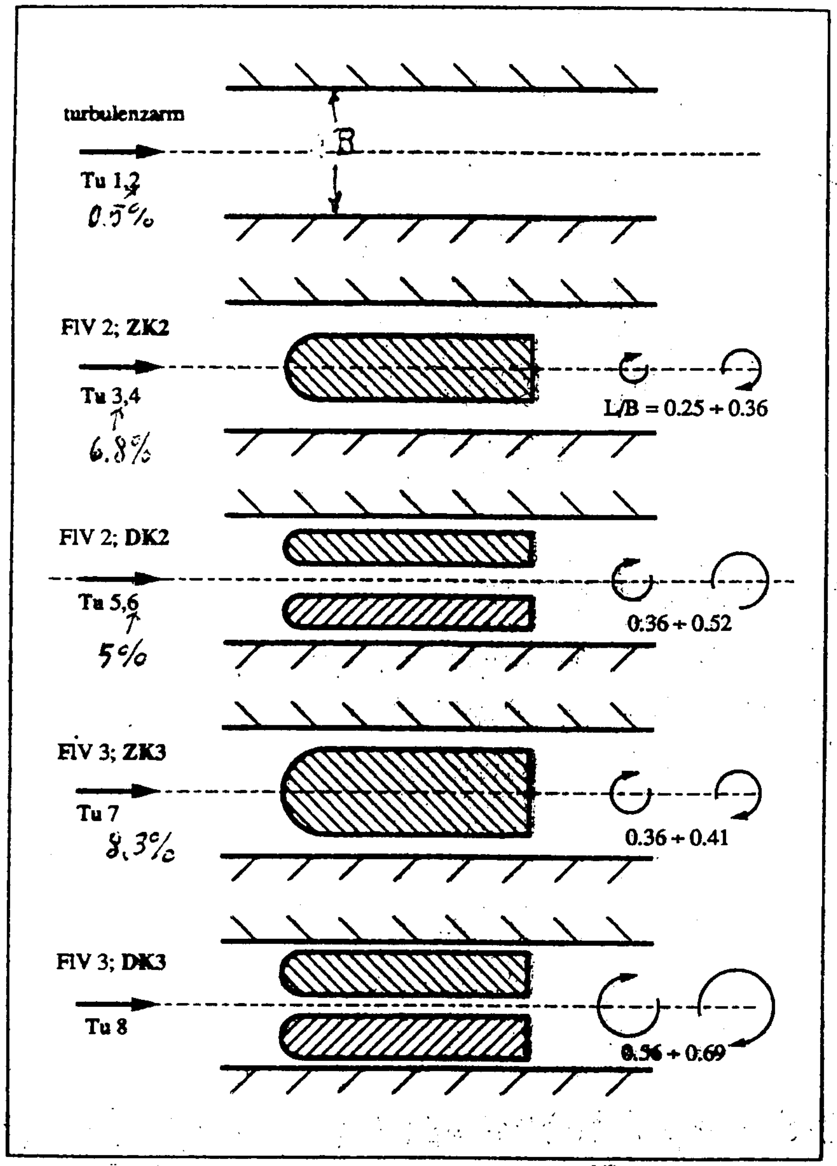
Kruemmer Flaechenverhaeltnis 1.5:◇ 1.0:□

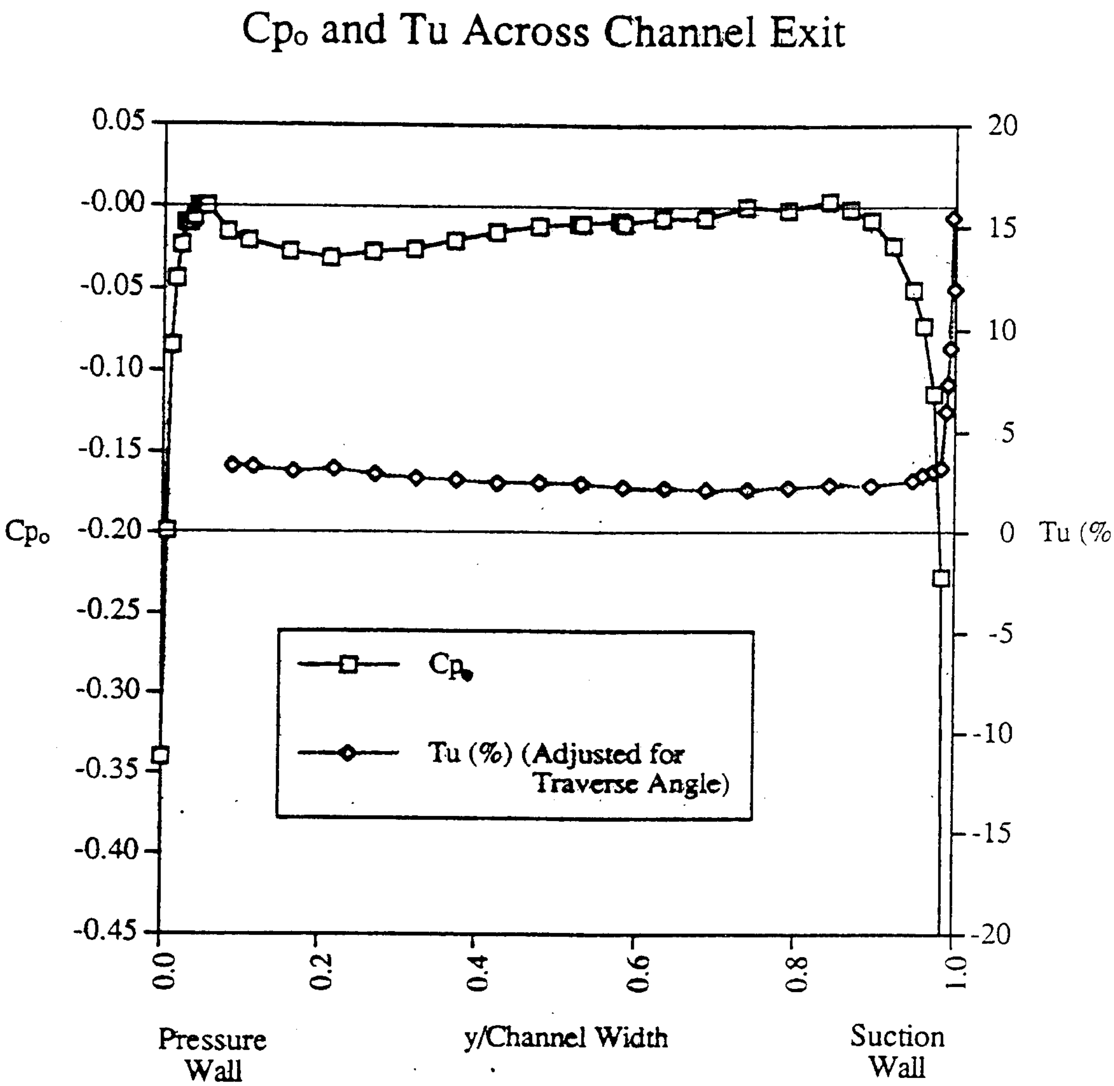
Turbulenzfall 3 IMT ETH 5-FEB-90

Abb.5.7.4



Totaldruckdifferenz Austritt - Eintritt


turbulenzarm
B
Tu 1,2
0.5%
FlV 2; ZK2
Tu 3,4
6.8%
L/B = 0.25 ÷ 0.36
FlV 2; DK2
Tu 5,6
5%
0.36 ÷ 0.52
FlV 3; ZK3
Tu 7
8.3%
0.36 ÷ 0.41
FlV 3; DK3
Tu 8
0.56 ÷ 0.69



$$C_{p_o} = \frac{P_o - P_{oi}}{P_{oi} - P_{si}} \qquad Tu = \frac{u'}{U}$$

WORKSHOP ON INHERENT NON STEADINESS IN COMPRESSORS AND TURBINES

PURDUE UNIVERSITY
OCTOBER 4-6, 1993

M.G. DUNN
CALSPAN ADVANCED TECHNOLOGY CENTER
BUFFALO, NEW YORK 14052

UNSTEADY FLOWS AND MEASUREMENTS

(WAKES, BOUNDARY LAYERS, CLEARANCE FLOWS, CAVITY FLOWS, MULTIPLE PRESSURE GRADIENTS, FREE STREAM TURBULENCE)

- WHY ARE WE INTERESTED ?
- UNDER WHAT CONDITIONS MIGHT THEY BE IMPORTANT? WHERE?
- MEASUREMENT STATE-OF-THE-ART
- TYPICAL DATA FROM SHORT-DURATION EXPERIMENT
- SUMMARY COMMENTS

ARE UNSTEADY EFFECTS IMPORTANT ?

- SMALL AMOUNT OF EXPERIMENTAL DATA AVAILABLE
- WHY DO WE FEEL THAT THEY MAY BE IMPORTANT FOR THE TURBINE ?
  1) AERODYNAMICS
     a) COOLING EFFECTIVENESS
     b) HEAT TRANSFER
     c) STRUCTURAL
  2) PERFORMANCE
- SOME OF THE IMPORTANT PARAMETERS
  1) VANE EXIT MACH NUMBER, SUBSONIC OR TRANSONIC
  2) ROTOR/STATOR SPACING
  3) ROTOR/ROTOR SPACING
  4) TIP CLEARANCE
  5) VANE INLET UNSTEADINESS

MEASUREMENT STATE-OF-THE-ART (TURBINES)

- SEVERAL U.S. GROUPS HAVE EXPERIENCE AND HAVE GENERATED APPLICABLE DATA:

  1) LONG RUN TIME
     a) UTRC LARGE SCALE ROTATING RIG (DRING, BLAIR, ETC.)

  2) SHORT-DURATION FACILITIES
     a) MIT BLOWDOWN FACILITY (EPSTEIN, ABHARI, ETC.)
     b) CALSPAN (CALSPAN UB RESEARCH CENTER), SHOCK-TUNNEL FACILITY (DUNN, ETC.)

UNSTEADY DATA FROM CALSPAN SHORT-DURATION FACILITIES

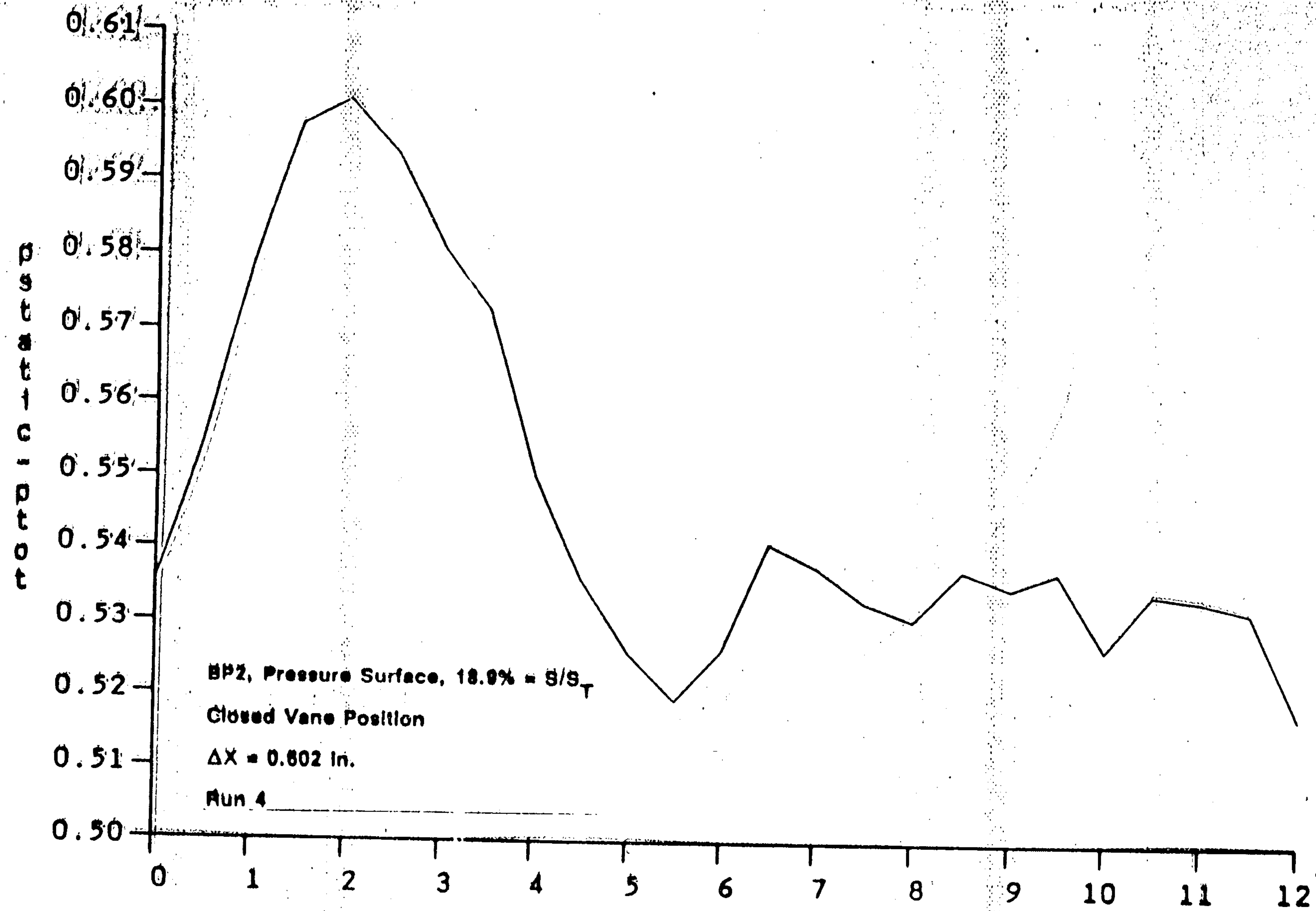
- PHASE-RESOLVED HEAT TRANSFER AND SURFACE PRESSURE ON THE BLADE OF THE ALLISON VBI TURBINE:

  a) VANE FILM COOLING WAS NOT USED
  b) MEASUREMENTS OBTAINED FOR BOTH SUBSONIC AND TRANSONIC VANE EXIT MACH NUMBER
  c) JOINT PROGRAM BETWEEN CALSPAN AND ALLISON
  d) DELANEY WILL DESCRIBE THIS PROGRAM IN MORE DETAIL LATER IN THIS WORKSHOP

- PHASE-RESOLVED HEAT TRANSFER ON THE BLADE OF THE FOLLOWING TURBINES:

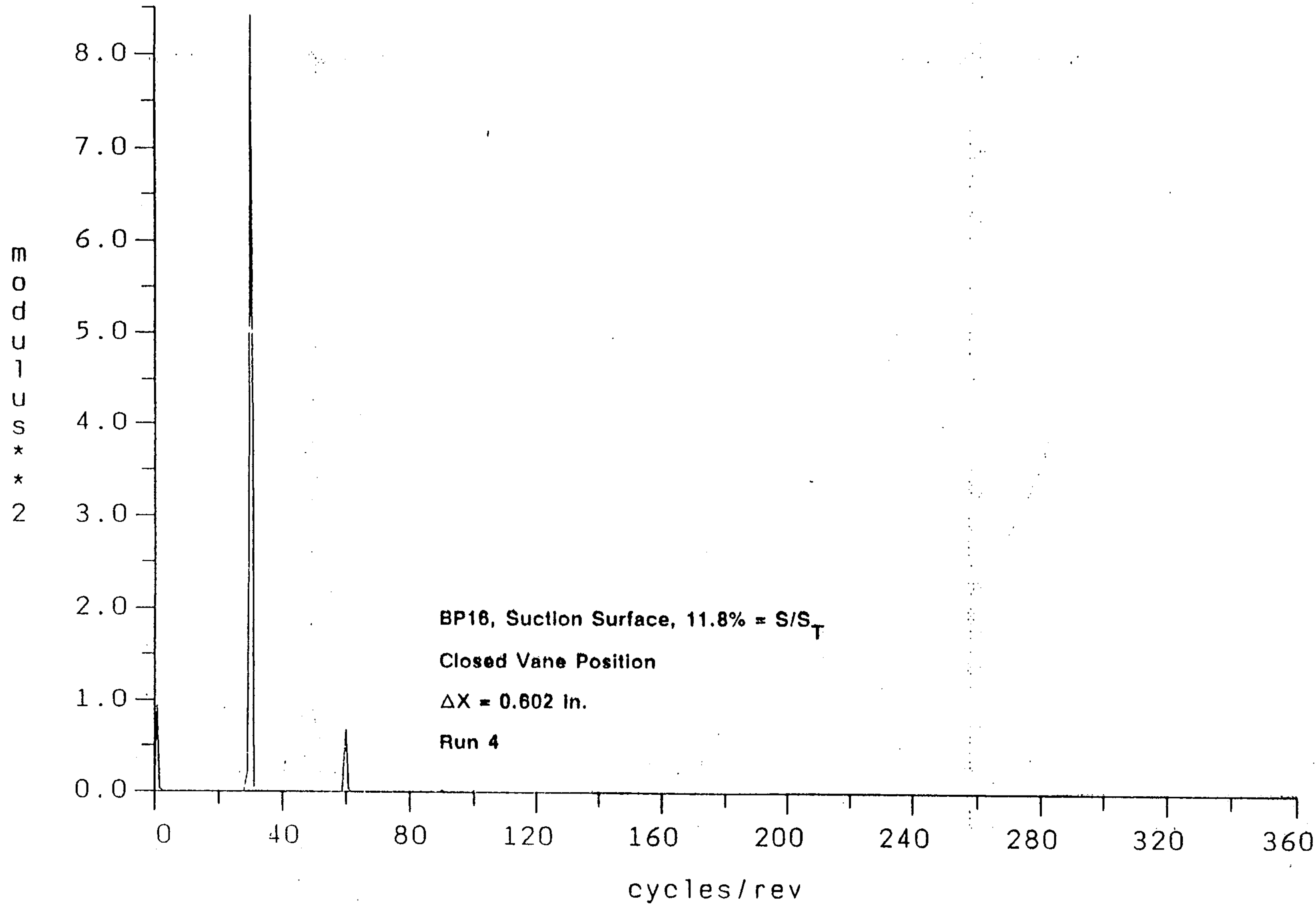
  a) TELEDYNE 702 HPT (LIMITED ON-BLADE PRESSURE DATA)
  b) GARRETT TFE731-2 HPT

- CURRENTLY DOING PHASE-RESOLVED HEAT TRANSFER AND SURFACE PRESSURE ON THE BLADE OF THE SSME FUEL-SIDE TURBOPUMP



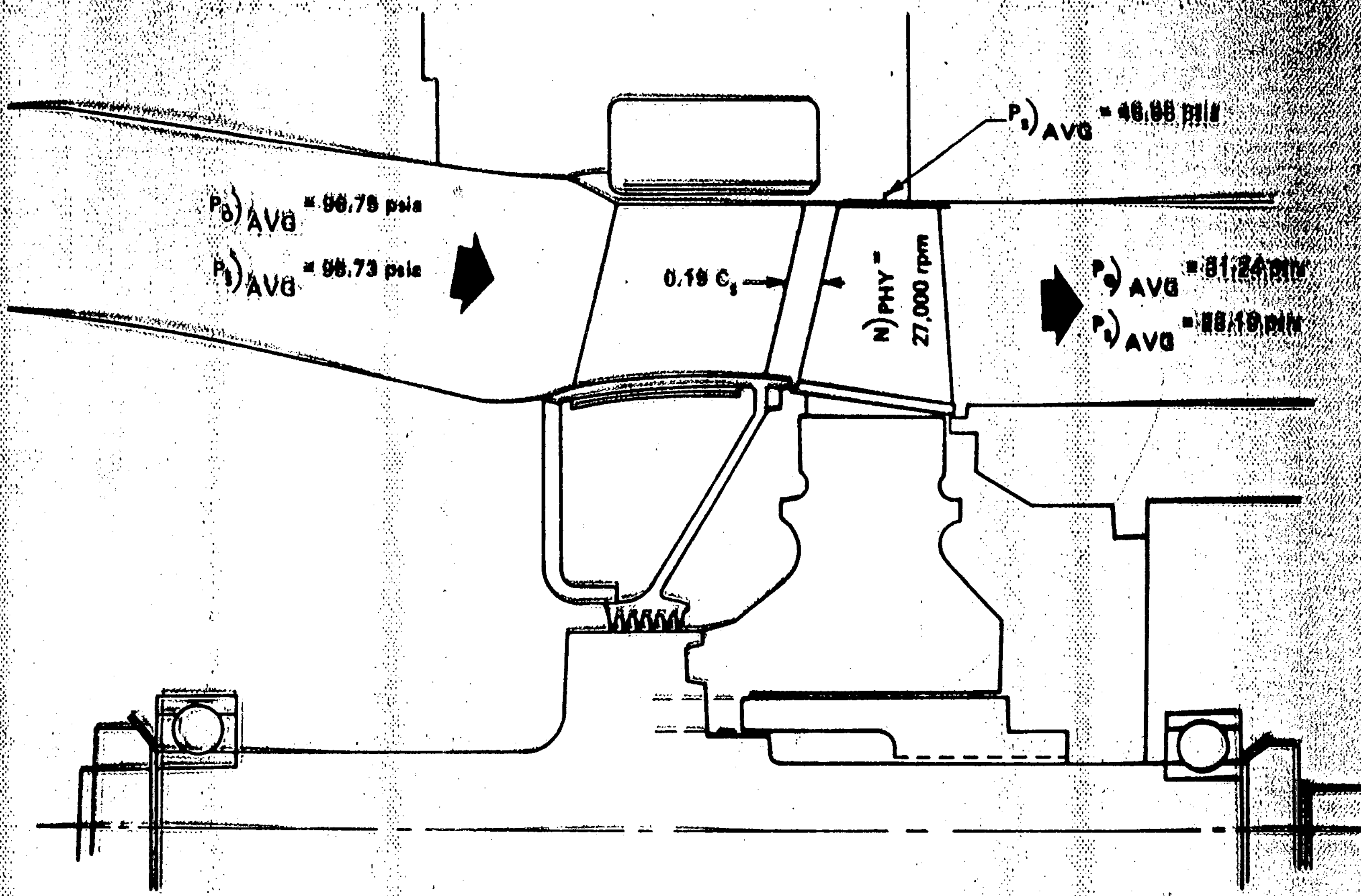
ENSEMBLE AVERAGE OF PRESSURE DATA FOR BLADE

ALLISON DATA

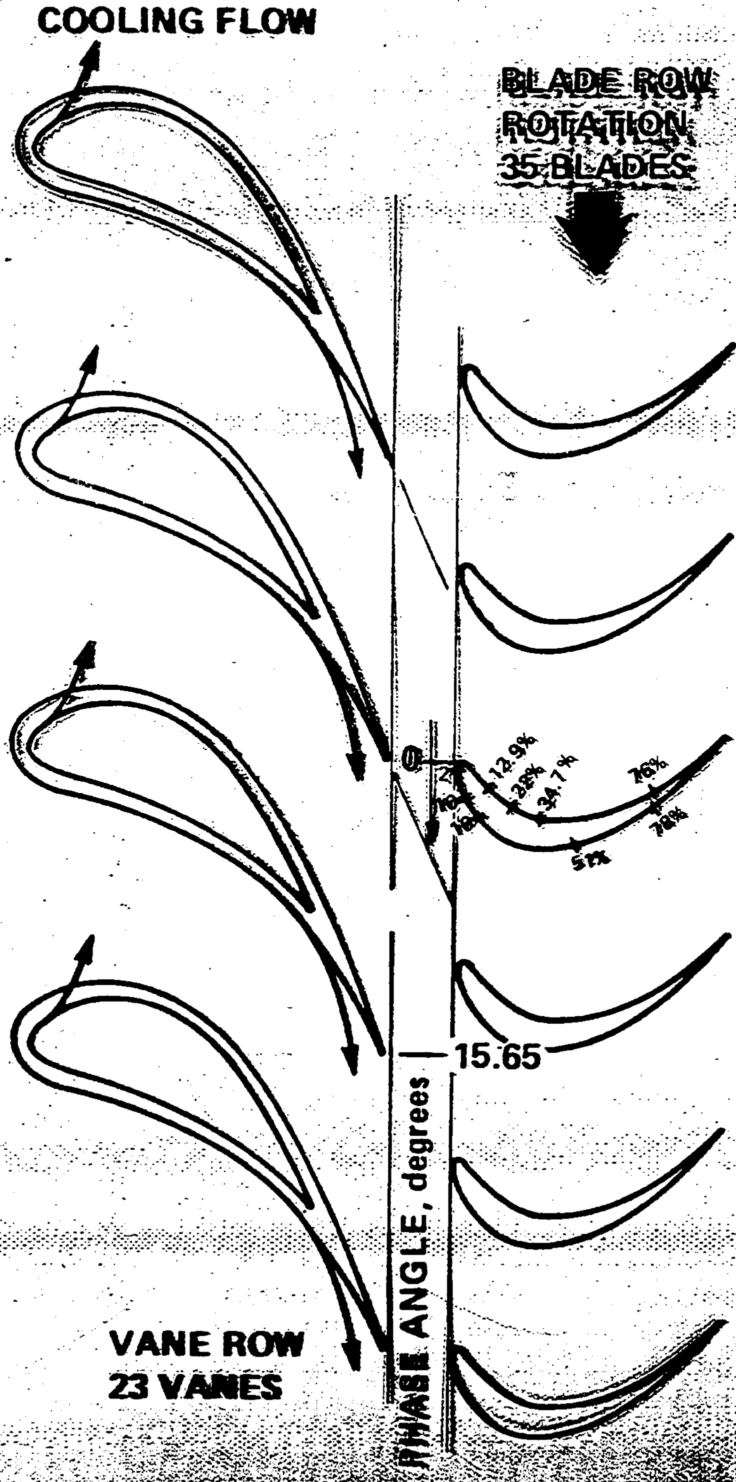


FFT OF PRESSURE DATA ON BLADE

ALLISON DATA

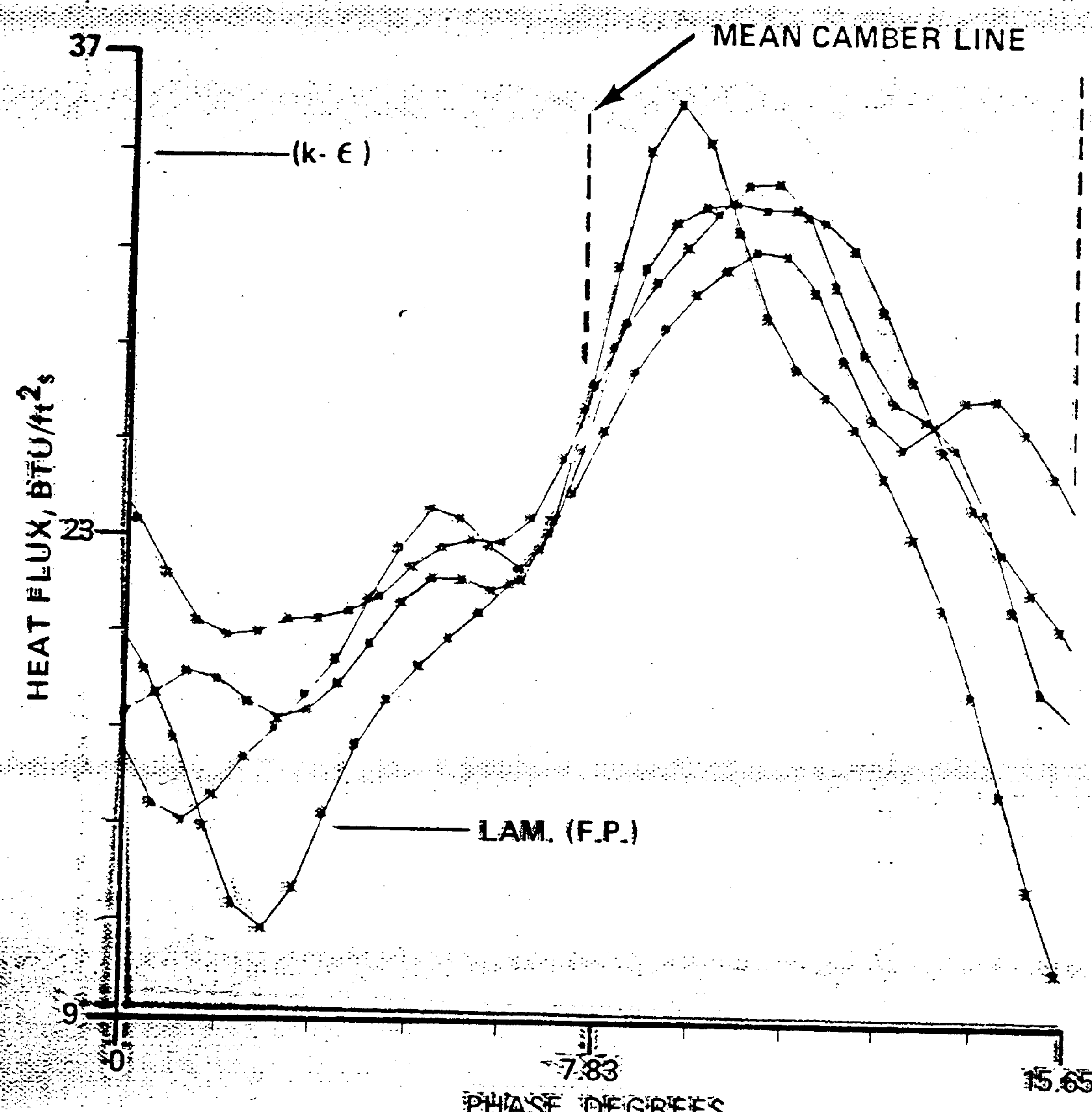


SKETCH OF STAGE CONFIGURATION AND TIME-AVERAGED PRESSURES

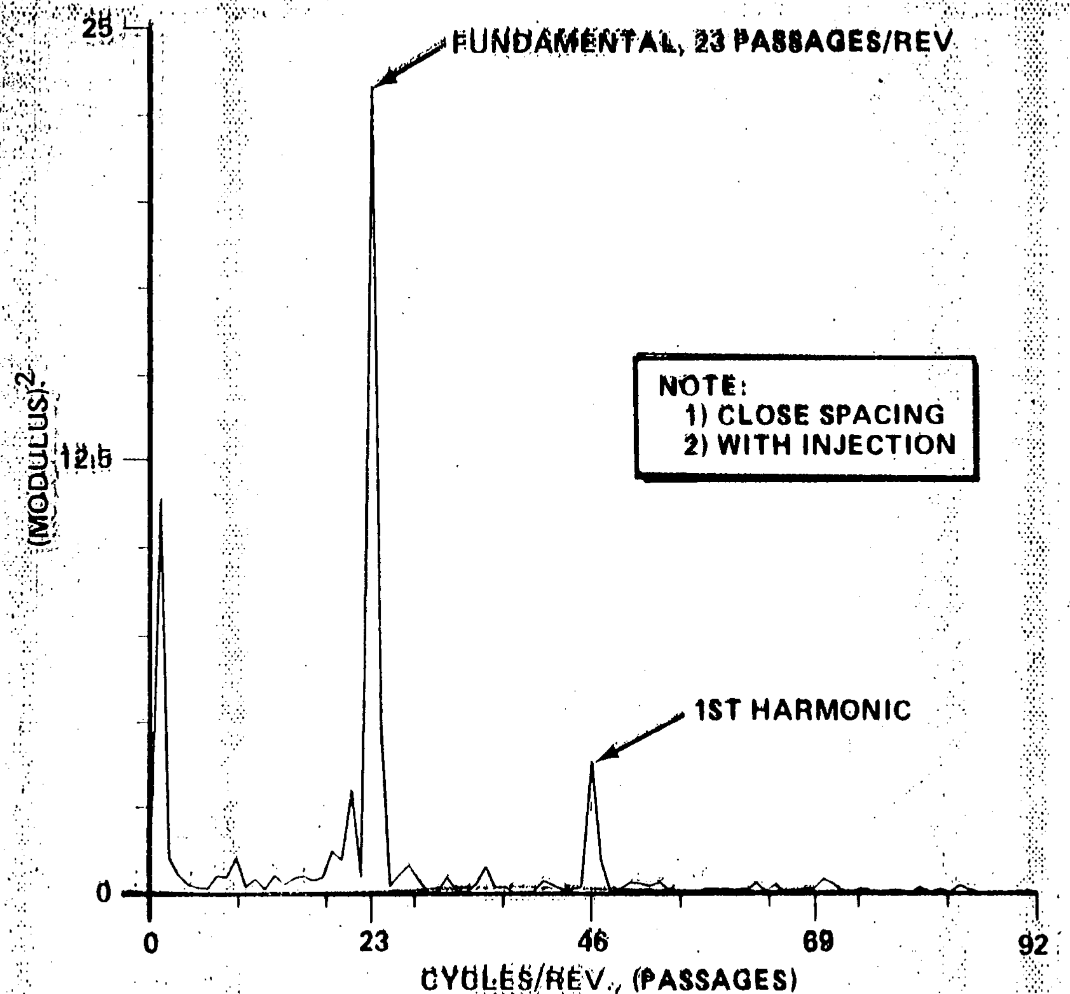


SKETCH OF STAGE AND PHASE ANGLE REFERENCE

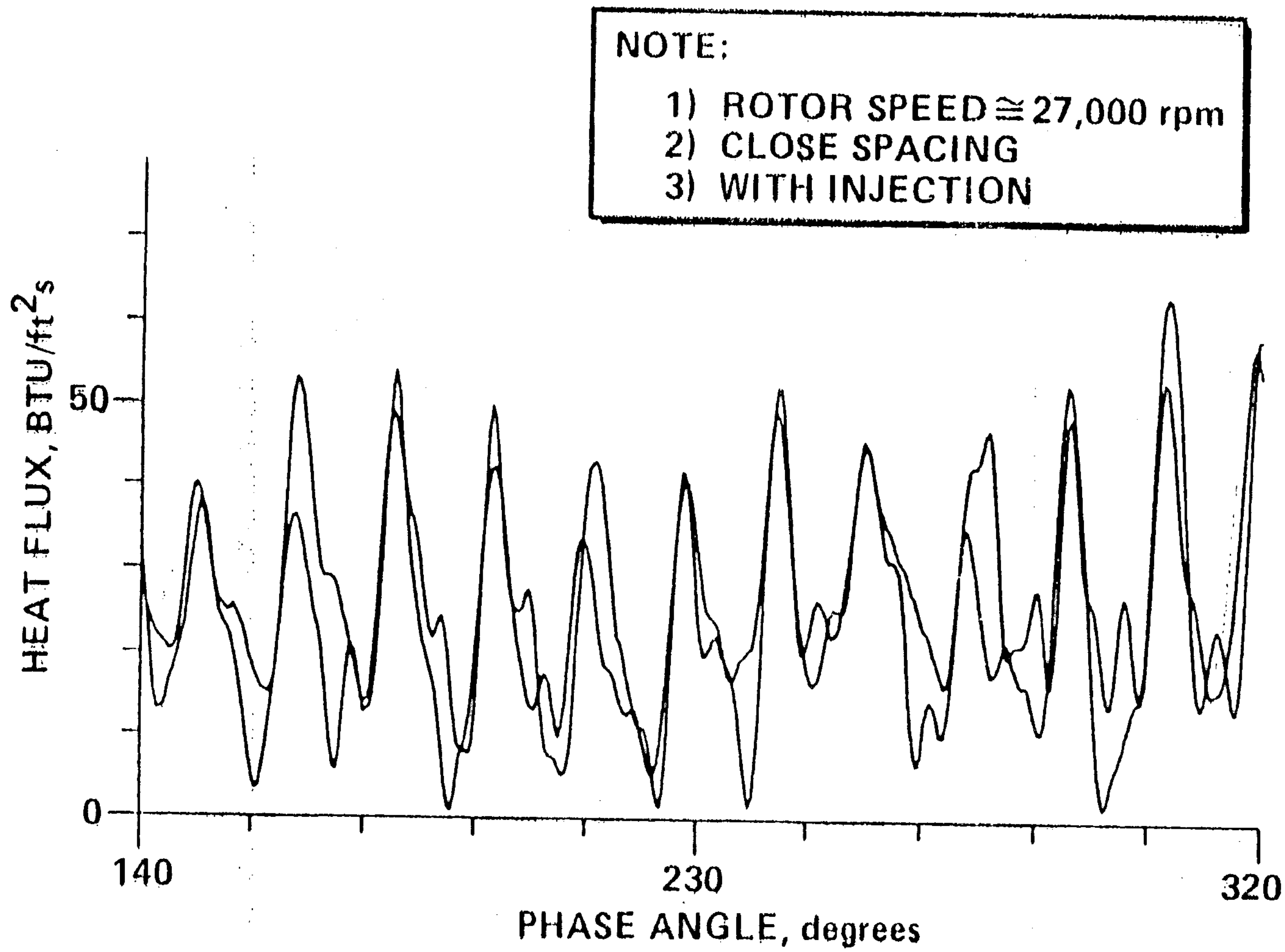
NOTE:
1) BLADE ROTATION IS CLOCKWISE LOOKING FROM FRONT
2) VANE PASSAGES TRAVERSED 11, 12, 13, 14
3) ROTOR SPEED ~ 27,000 rpm
4) CLOSE SPACING
5) NO INJECTION



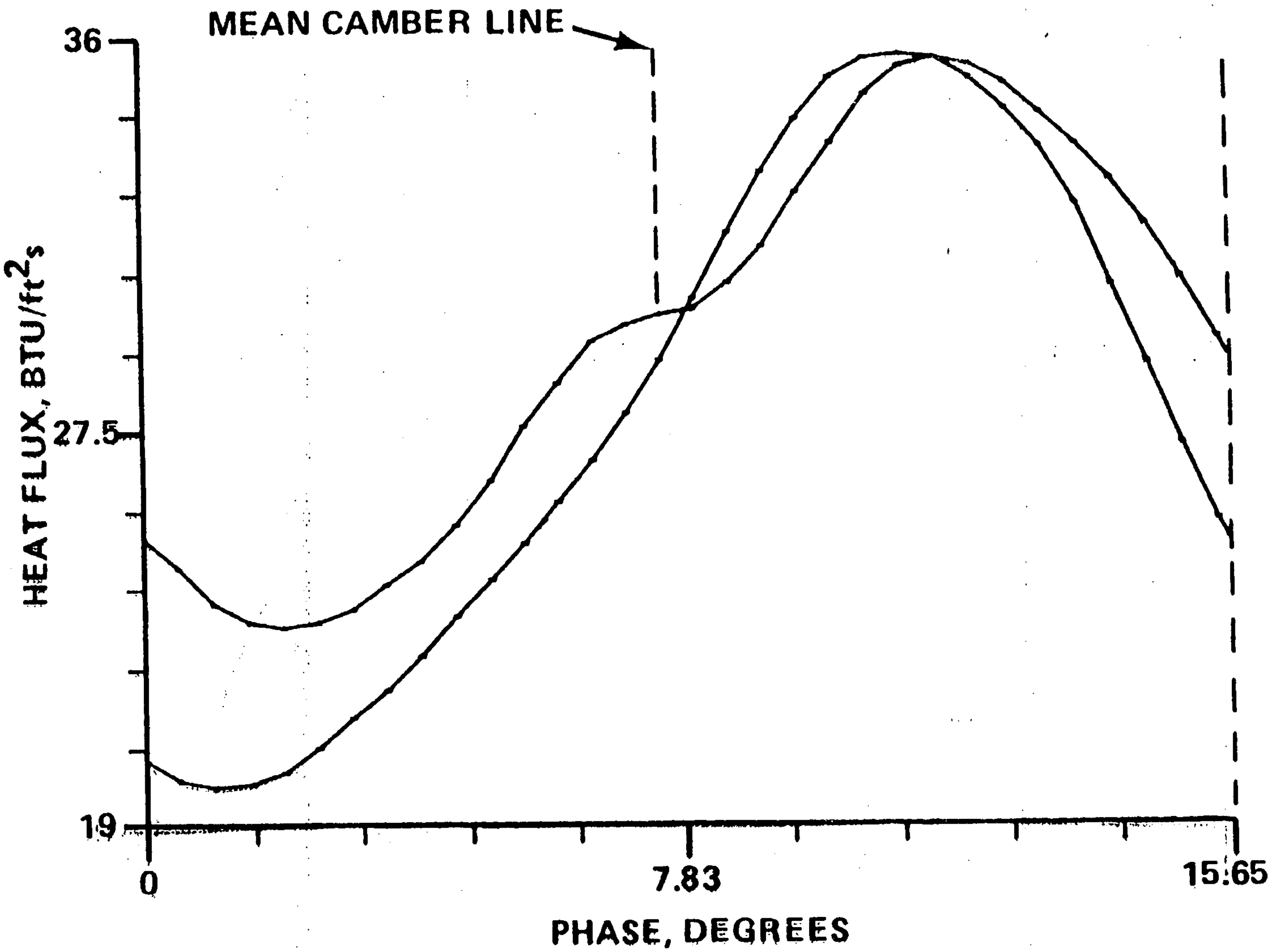
PHASE-RESOLVED HEAT-FLUX DATA AT 10% WETTED DISTANCE ON BLADE SUCTION SURFACE



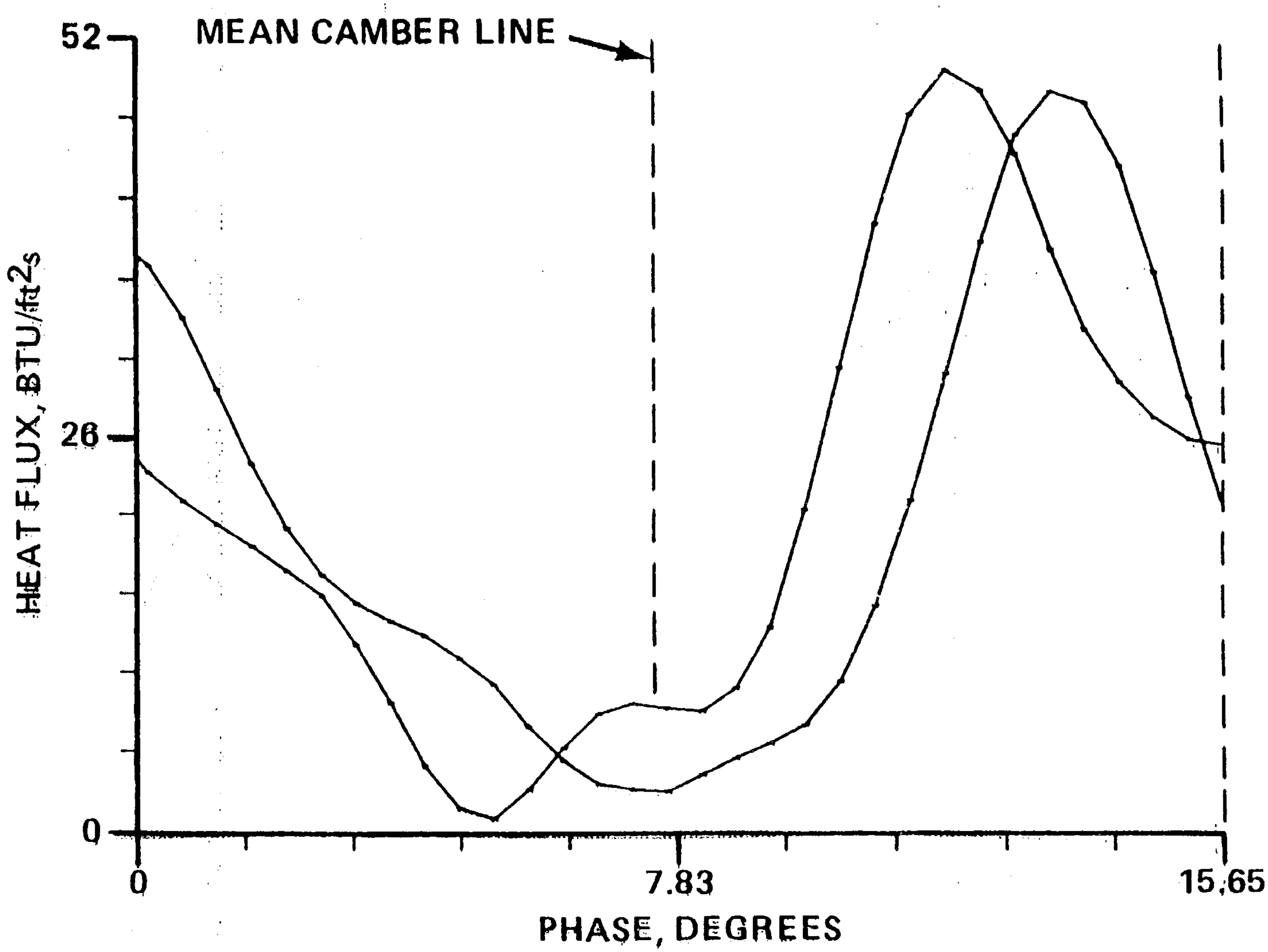
MODULUS OF FOURIER TRANSFORM OF HEAT FLUX DATA AT 10% WETTED DISTANCE ON BLADE SUCTION SURFACE



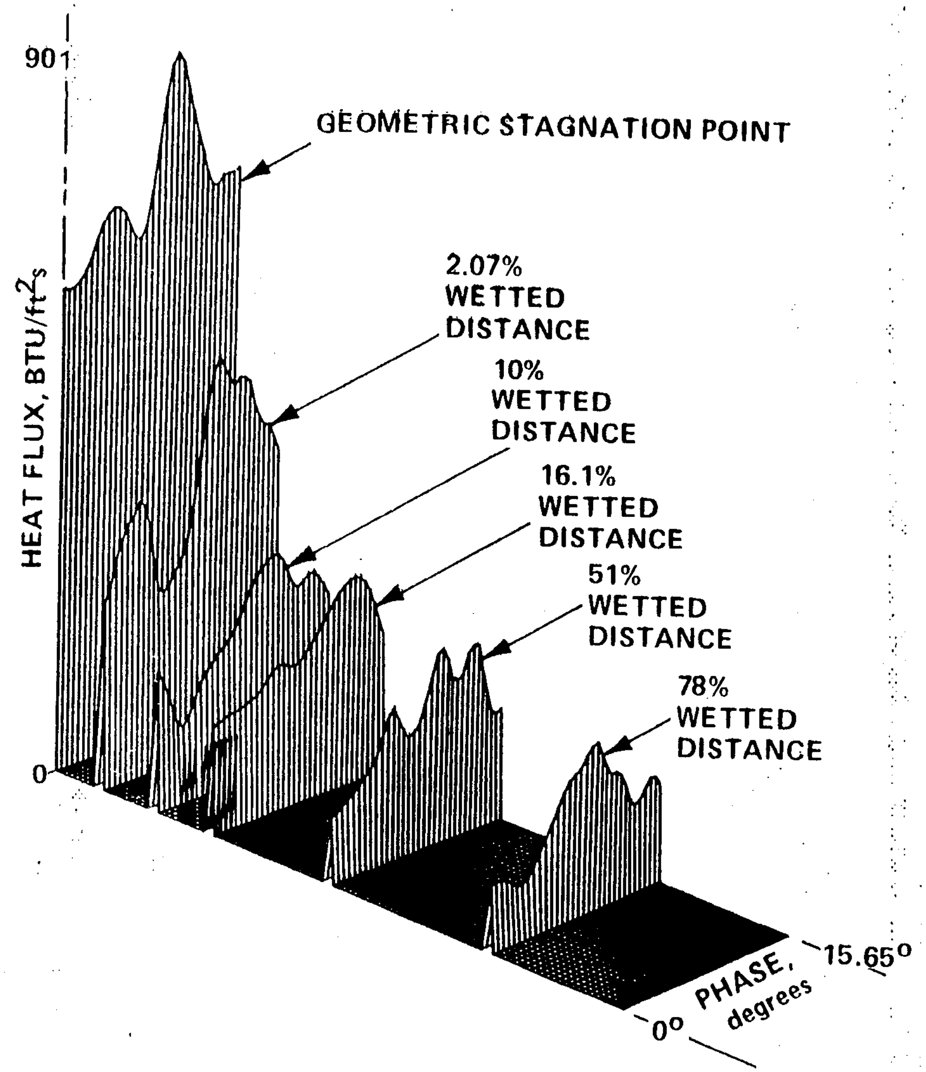
HEAT-FLUX HISTORY FOR TWO REVOLUTIONS OBTAINED AT 10% WETTED DISTANCE ON BLADE SUCTION SURFACE



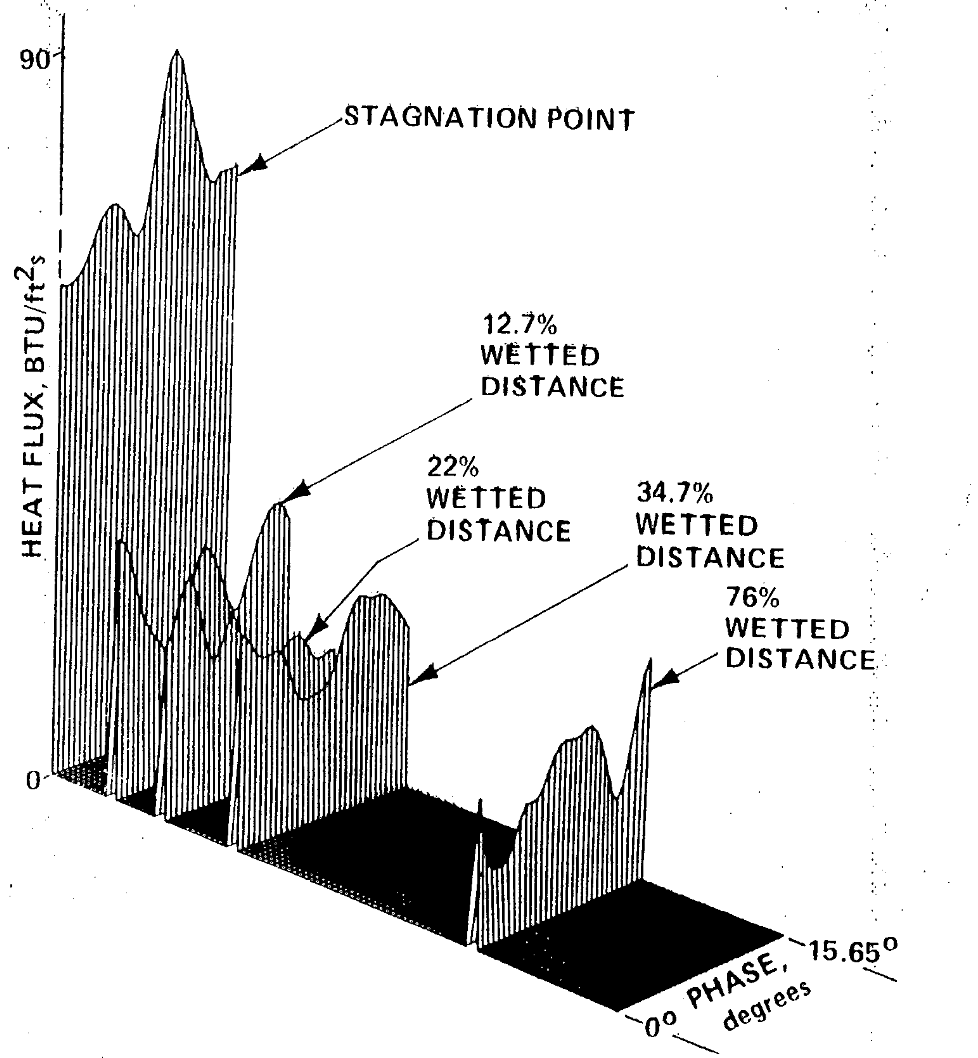
PHASE-RESOLVED HEAT-FLUX DATA AT 2.07% WETTED DISTANCE ON BLADE SUCTION SURFACE FOR PASSAGE #1 ON SUCCESSIVE REVOLUTIONS



PHASE-RESOLVED HEAT-FLUX DATA AT 10% WETTED DISTANCE ON BLADE SUCTION SURFACE FOR PASSAGE #13 ON SUCCESSIVE REVOLUTIONS



PHASE-RESOLVED CONTOUR PLOT OF HEAT-FLUX DISTRIBUTION ON BLADE SUCTION SURFACE



PHASE-RESOLVED CONTOUR PLOT OF HEAT-FLUX DISTRIBUTION ON BLADE PRESSURE SURFACE

SUMMARY COMMENTS

- THERE IS REASON TO BELIEVE THAT UNSTEADY EFFECTS MAY BE IMPORTANT

- THE ANALYTICAL STATE-OF-THE-ART IS ADVANCING RAPIDLY BUT EXPERIMENTAL RESULTS ARE IN SHORT SUPPLY.

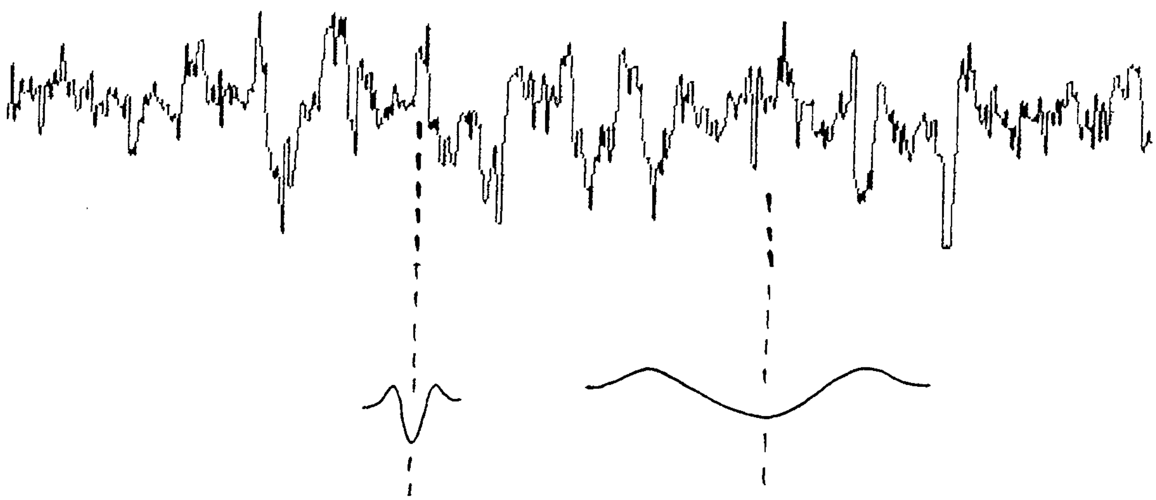
- THE EXPERIMENTAL STATE-OF-THE-ART IS CAPABLE OF PROVIDING THE DATA NOTED ABOVE. THE ANALYTICAL AND EXPERIMENTAL GROUPS MUST WORK CLOSELY TOGETHER TO MAKE MAJOR ADVANCEMENTS IN THE NEAR FUTURE.

SPECTRAL RESOLUTION OF NON-PERIODIC DATA: SOME USES OF WAVELETS.

Jacques Lewalle

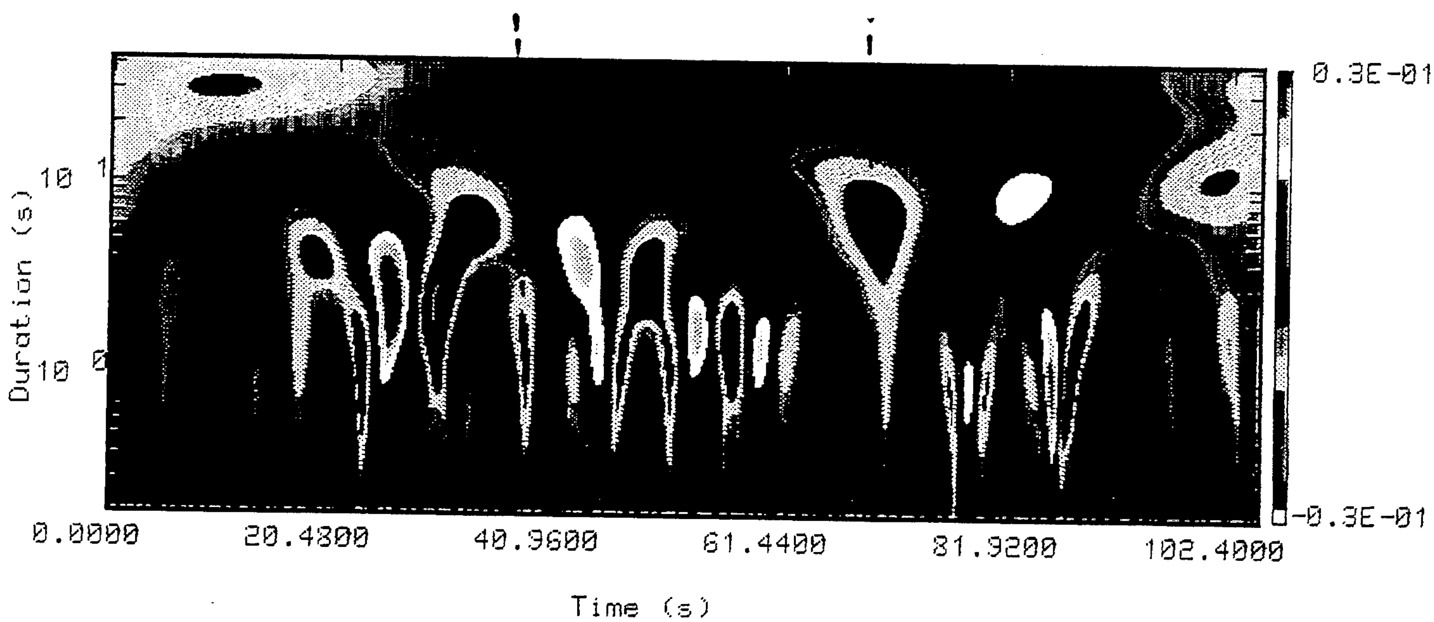
Associate Professor
Department of Mechanical Aerospace
and Manufacturing Engineering
Syracuse University, Syracuse, NY 13244-1240
e-mail: JLEWALLE@mailbox.syr.edu

PREPARED FOR AFOSR/WINCAT, Oct. 4-6, 1993.



$$f(\kappa,t) = \int_{-\infty}^{\infty} \kappa^{1/2} f(\tau) g(\kappa(\tau - t)) d\tau.$$

shape scale location

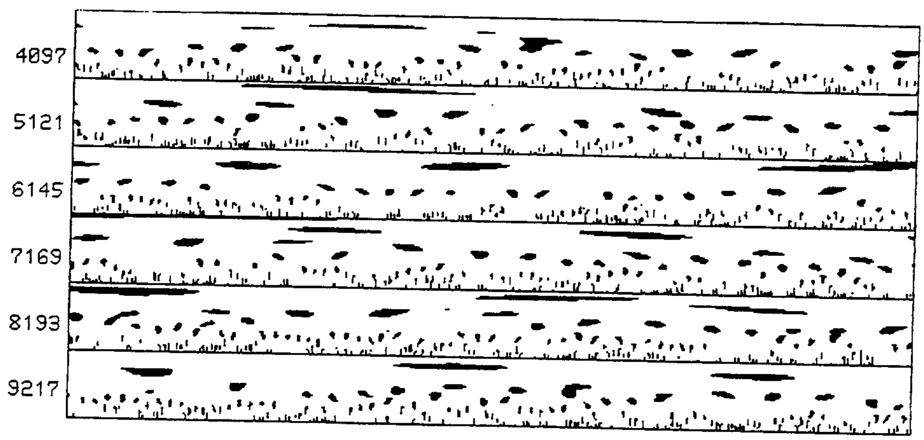


WAVELET SELECTION: GENERAL SHAPE IS IMPORTANT

NO OPTIMAL WAVELET FOR THESE APPLICATIONS

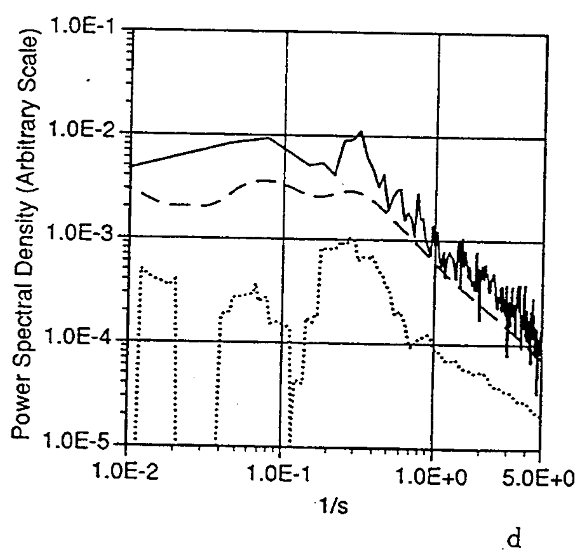
ENERGY MAPS (PARSEVAL)

STRUCTURE MAPS EVENT EDUCTION



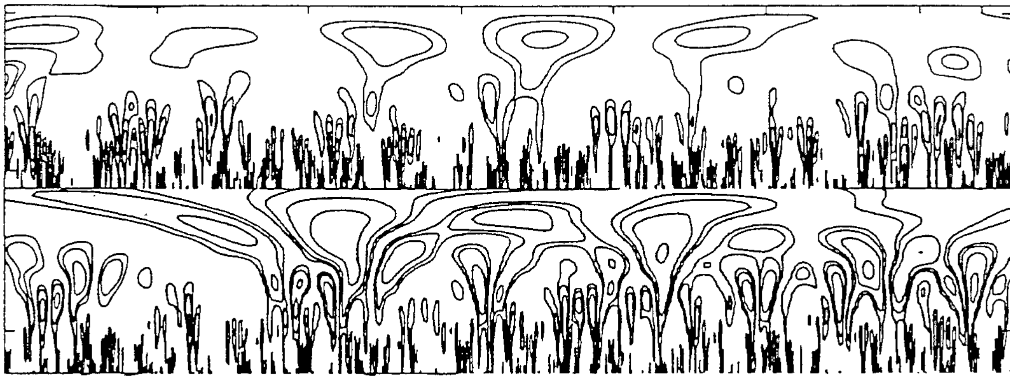
CONDITIONAL STATISTICS

ENERGY SPECTRA

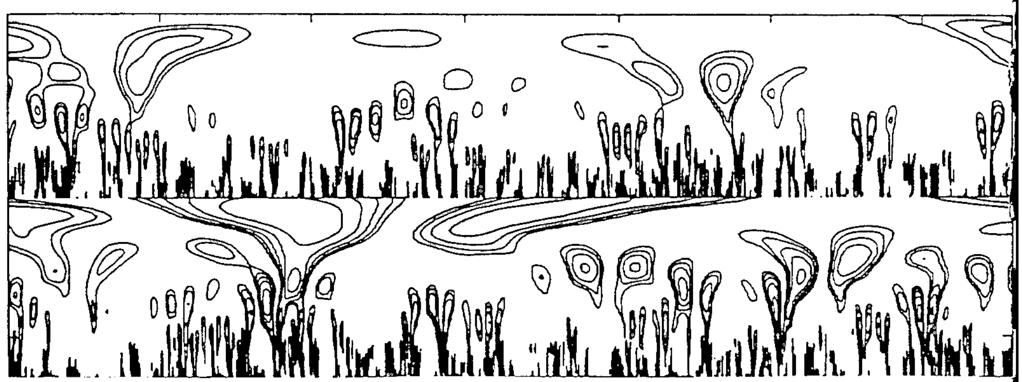


(FROM: HIGUCHI ET AL, 1993)

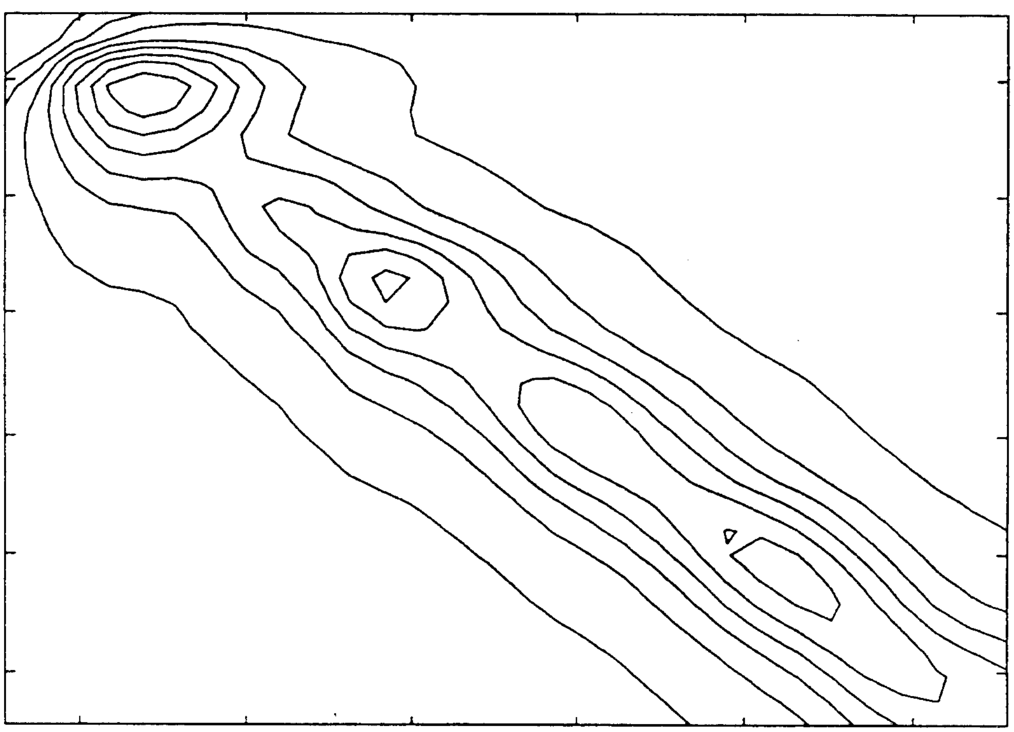
wS#, u=xp25yp53.dat: 1-15839



wS#, v=xp25yp53.dat: 1-15839



x=.25, y=.53, u=,v= spectral correlation



max=0.1150, min=-0.2550

CONCLUSIONS

The basic wavelet map lends itself to further processing.

- Parseval: time/duration distribution of energy.
- Inverse transform: filtering, etc.
- Shape dependence: pattern recognition.
- Structural information: conditional statistics
- Spectral correlations
- Etc.

Better than Fourier for non-periodic data.
Can be used on existing data.

Measurements of Surface Temperature and Heat Transfer Based on Laser-Induced Thermographic Phosphorescence

Mingking K. Chyu
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

Thermographic Phosphorescence

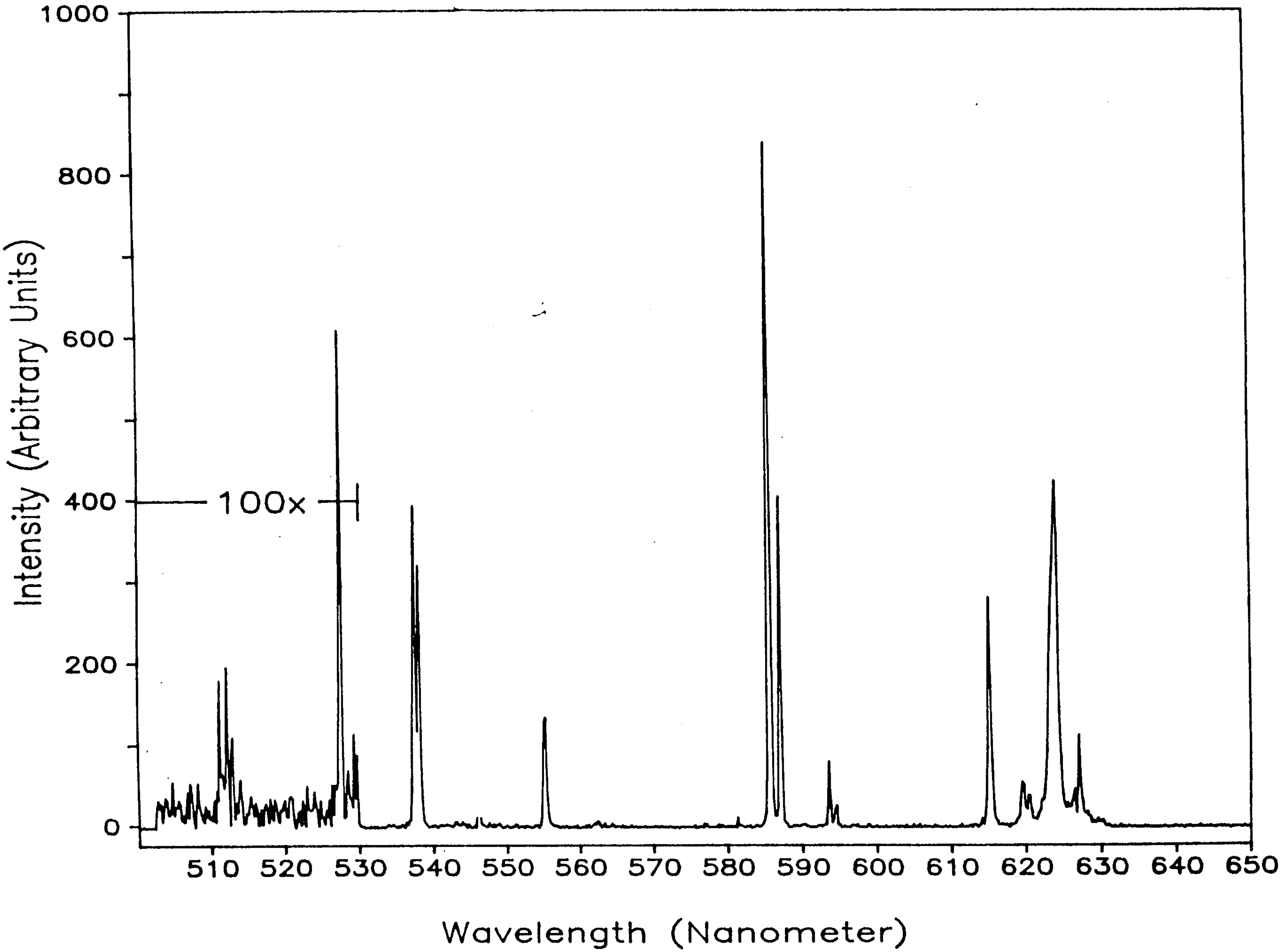
- Accuracy Comparable with Existing Techniques
- Non-intrusive, Optical Access
- Capable of (Simultaneous) Measurement of Temperature and Heat Transfer
- Potential for

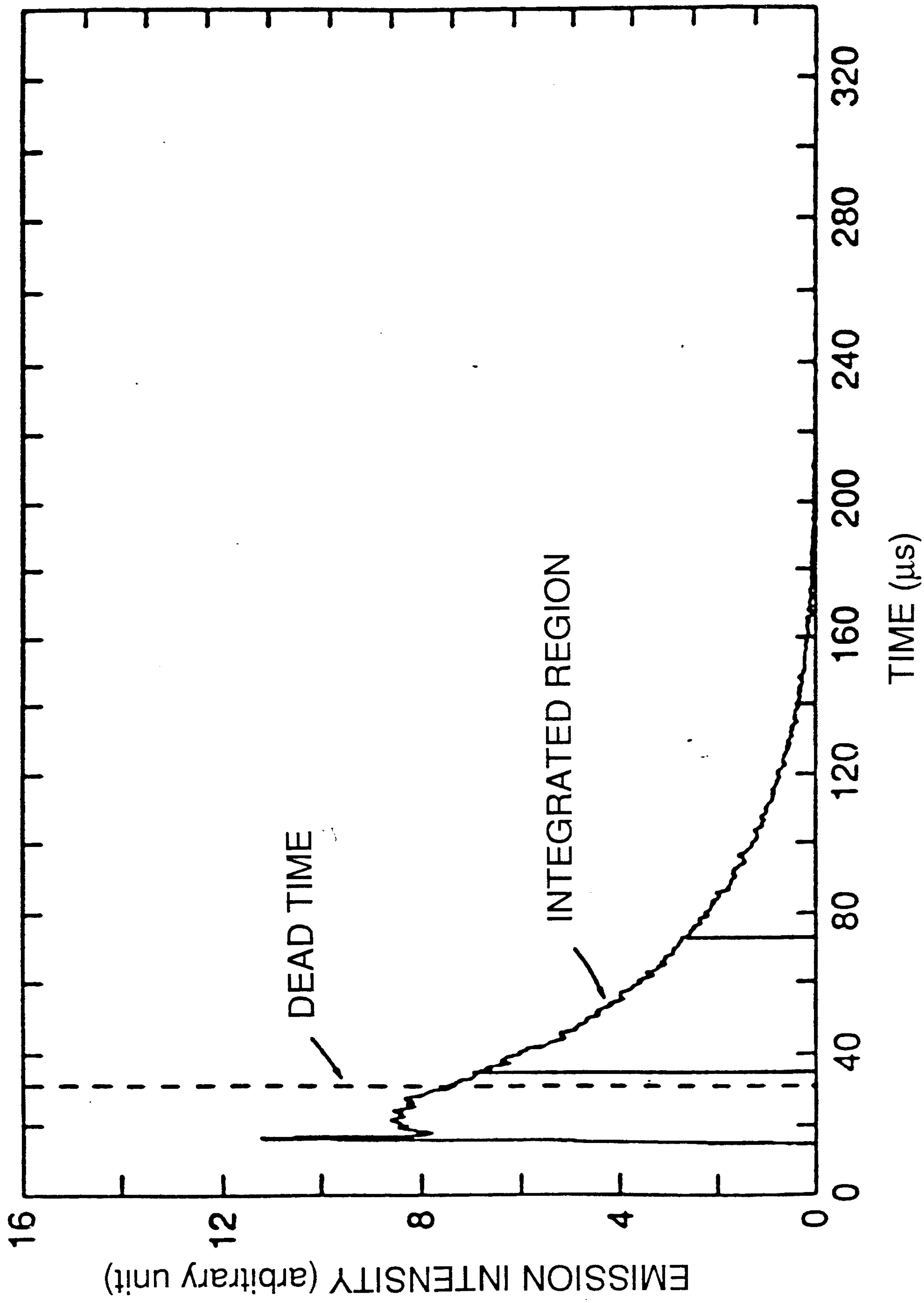
    Rapid Unsteady Phenomena

    Rotating Environment

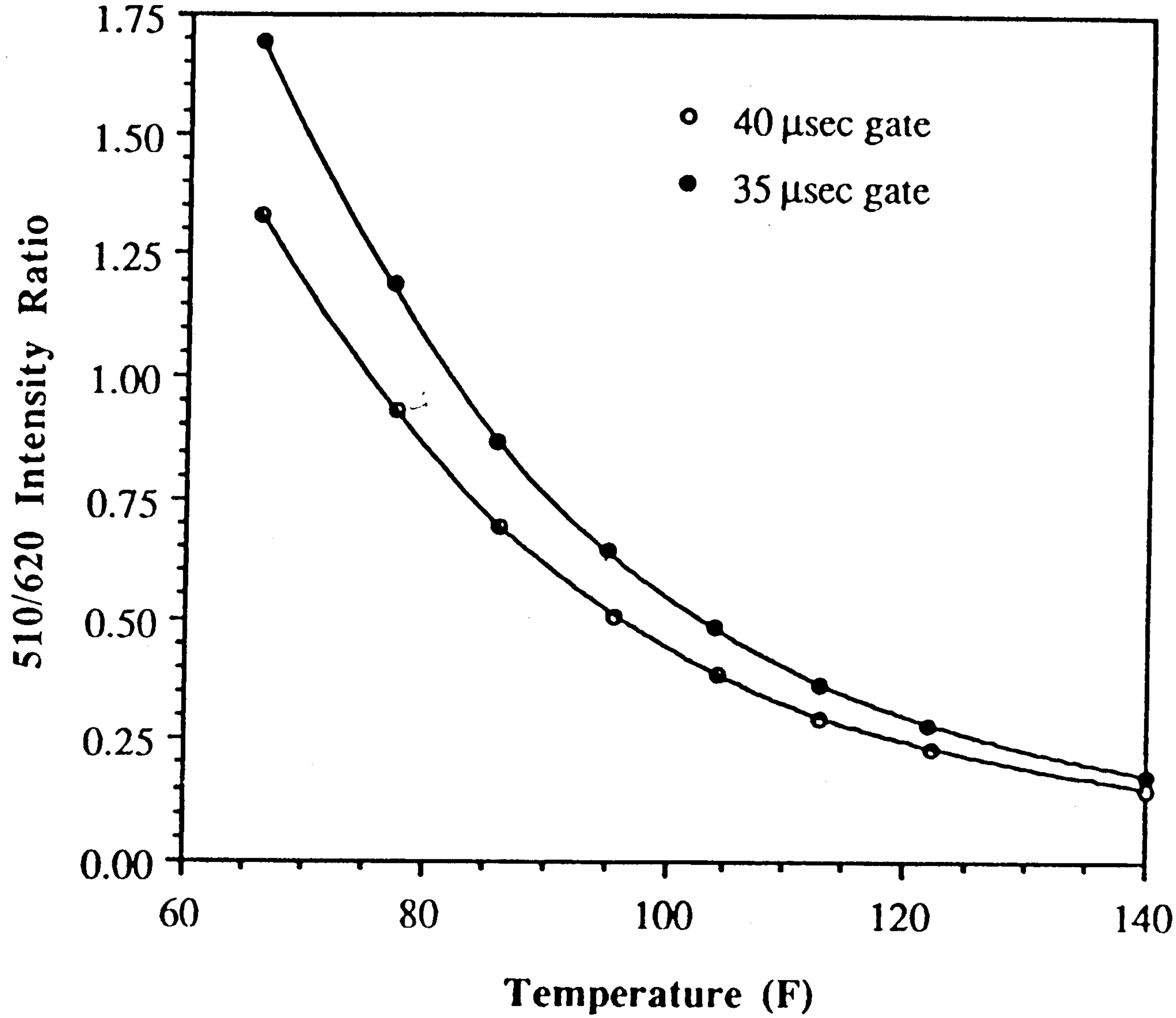
    High Temperature Environment

Emission Spectrum of $La_2O_2S:Eu^{+3}$ Phosphor



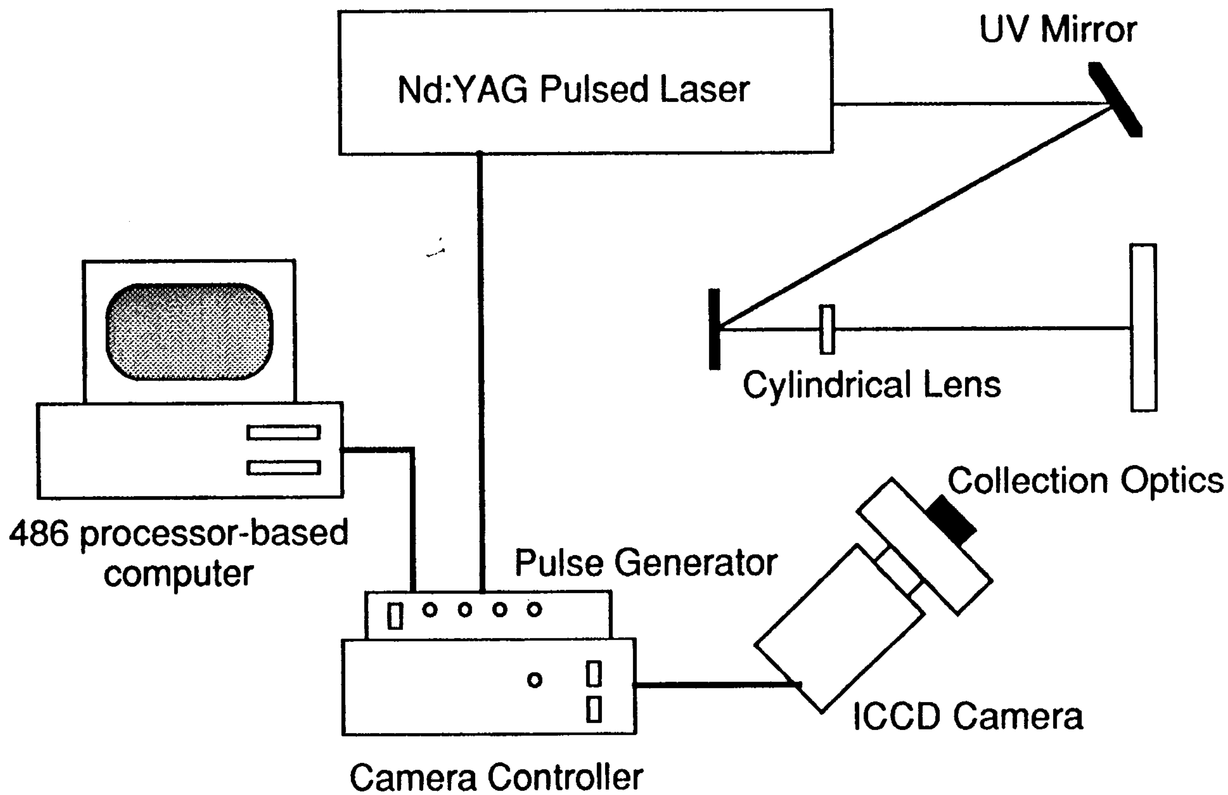


DEAD TIME
INTEGRATED REGION
EMISSION INTENSITY (arbitrary unit)
TIME (µs)
0
4
8
12
16
0
40
80
120
160
200
240
280
320

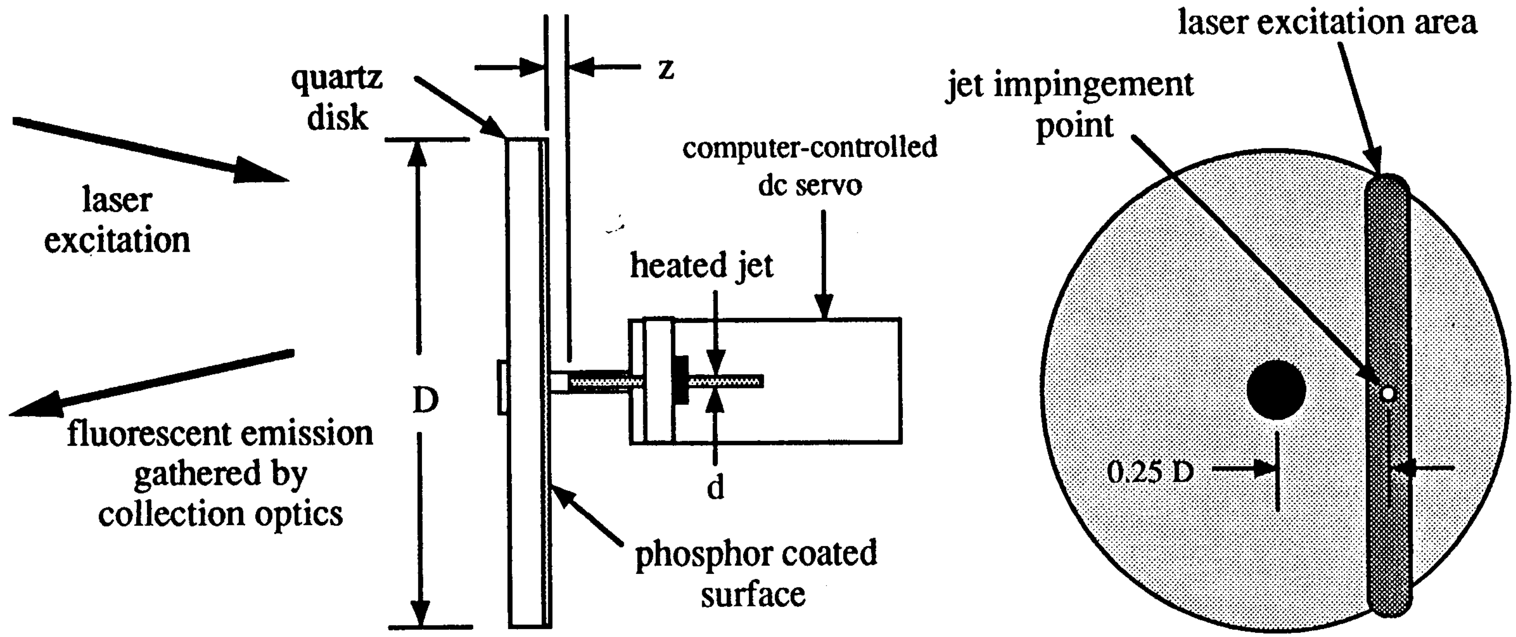


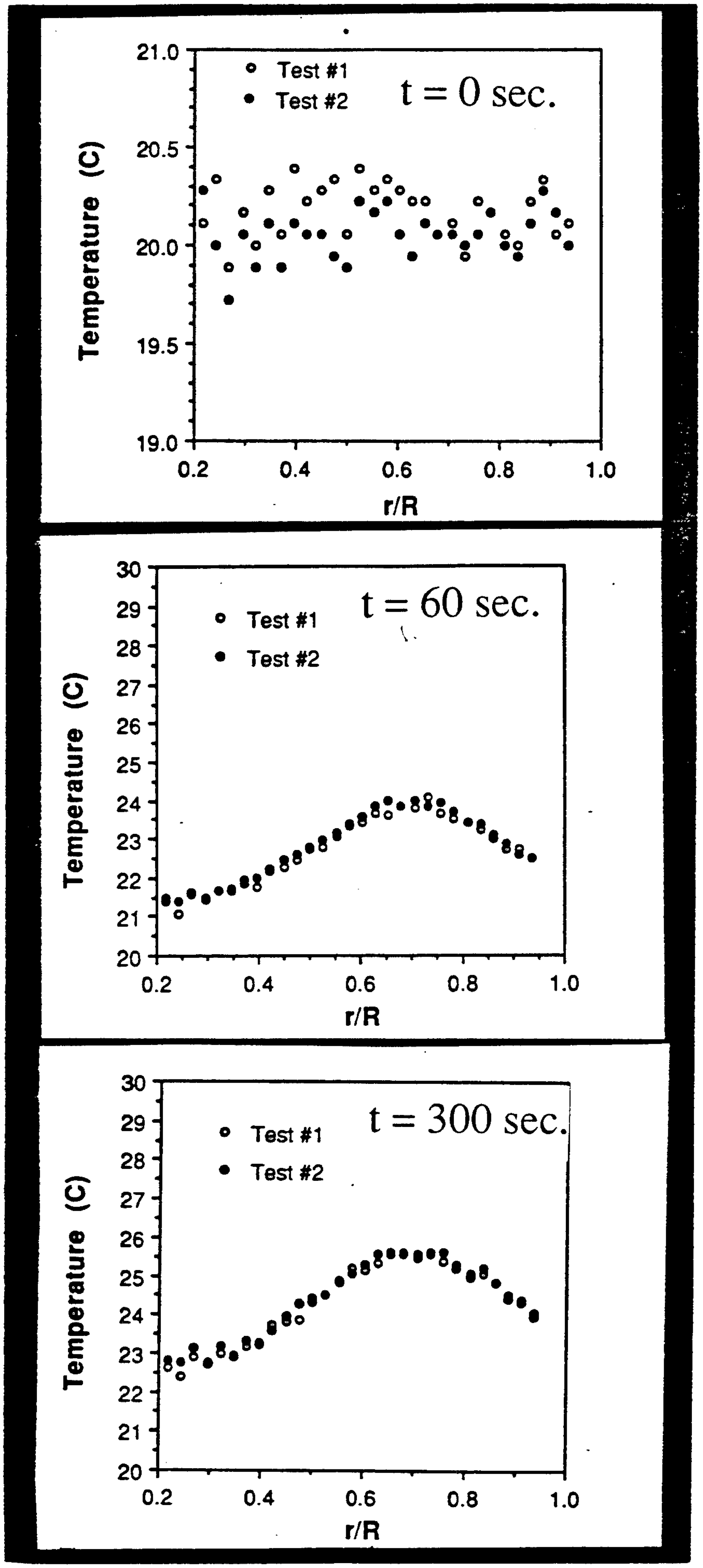
Phosphor Calibration Curves

Laser-Induced Fluorescence Thermal Imaging System

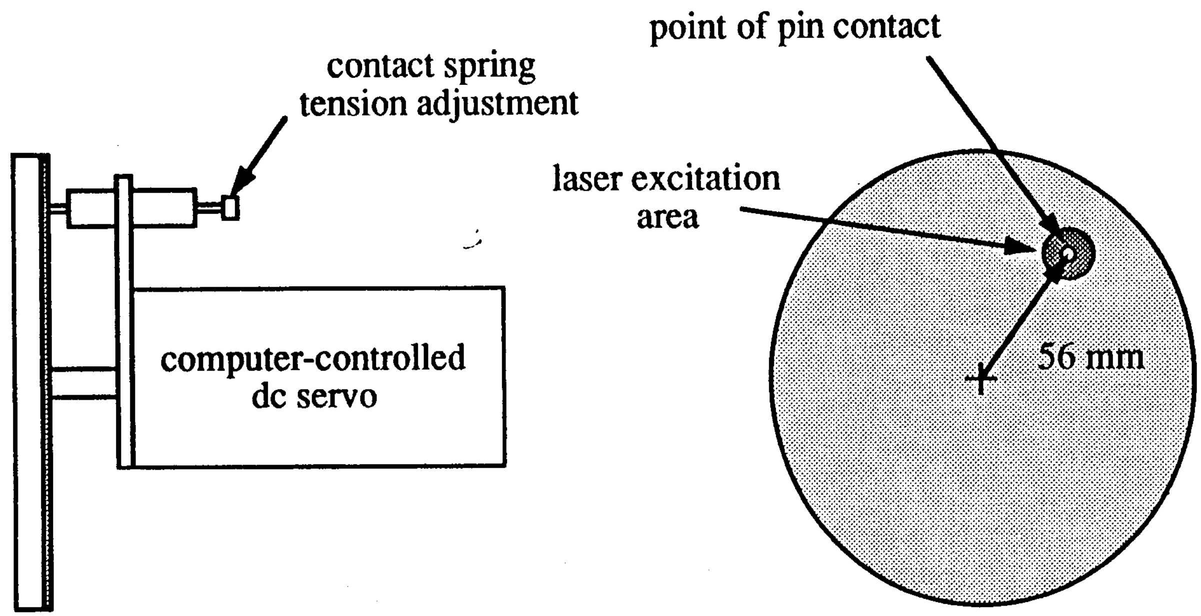


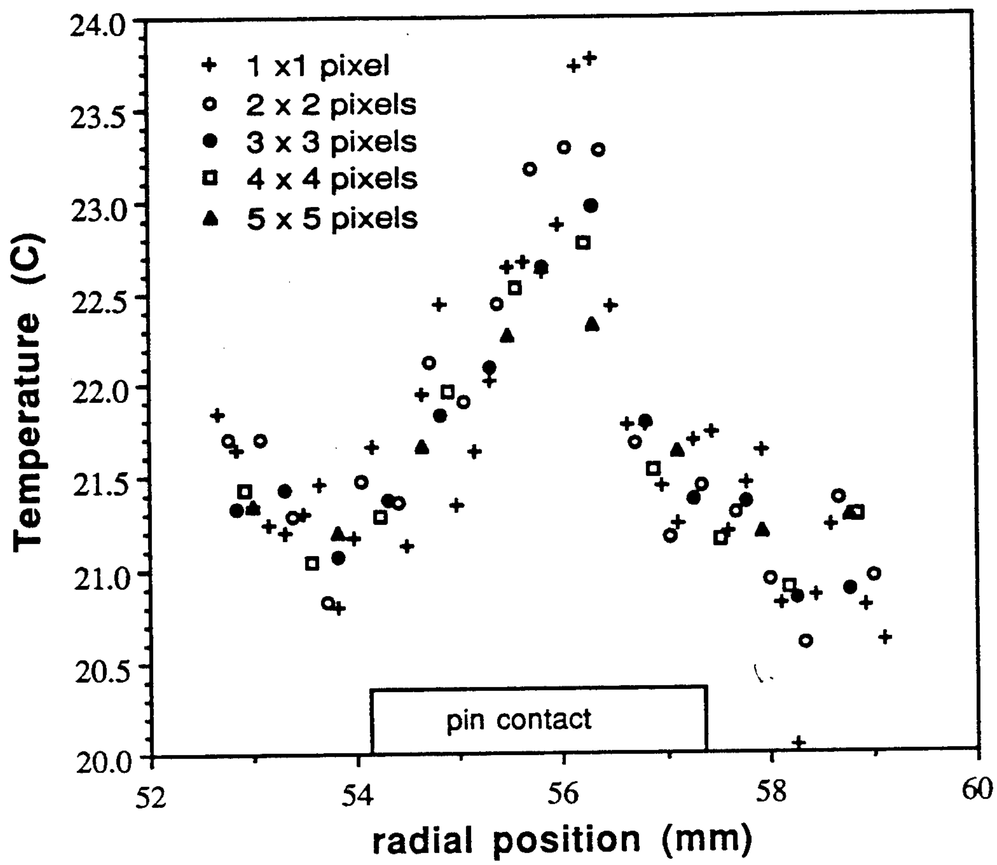
Case 1: Heated Jet Impingement Temperature Measurement

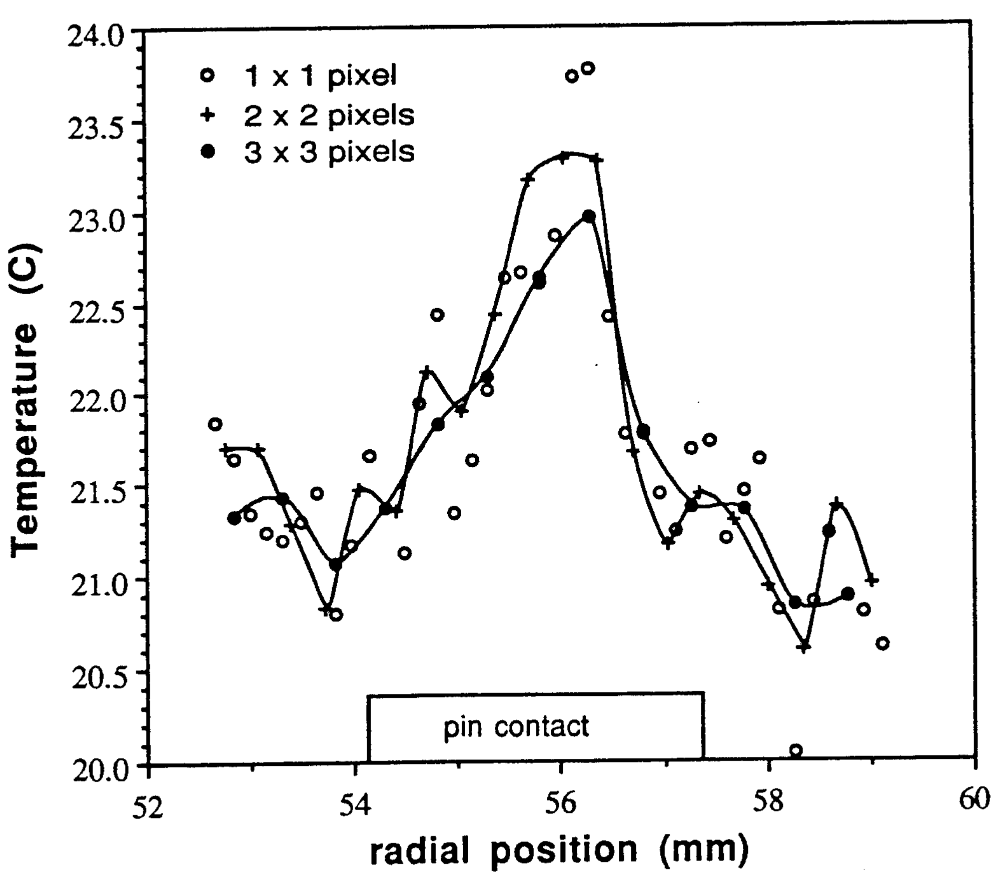



Test #1
Test #2
t = 0 sec.
Temperature (C)
21.0
20.5
20.0
19.5
19.0
0.2
0.4
0.6
0.8
1.0
r/R
Test #1
Test #2
t = 60 sec.
Temperature (C)
30
29
28
27
26
25
24
23
22
21
20
0.2
0.4
0.6
0.8
1.0
r/R
Test #1
Test #2
t = 300 sec.
Temperature (C)
30
29
28
27
26
25
24
23
22
21
20
0.2
0.4
0.6
0.8
1.0
r/R

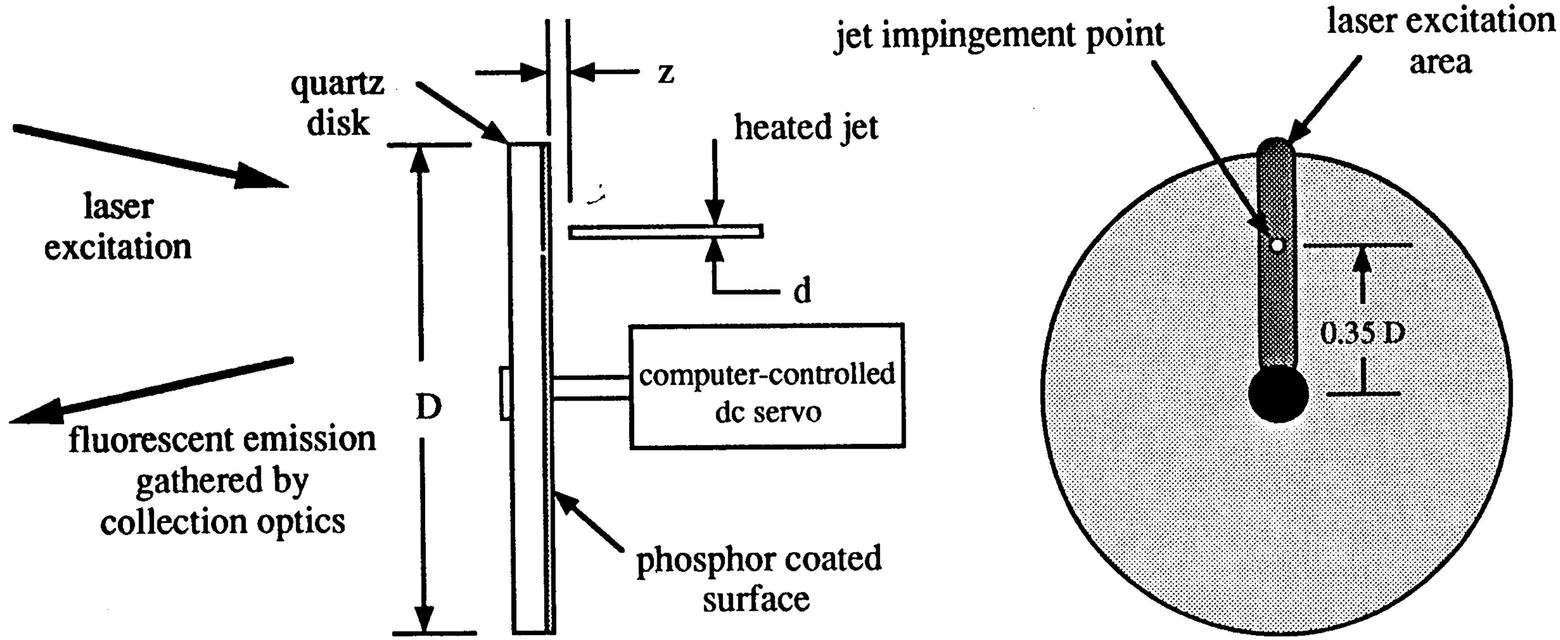
Case 2: Sliding-Contact Temperature Measurement

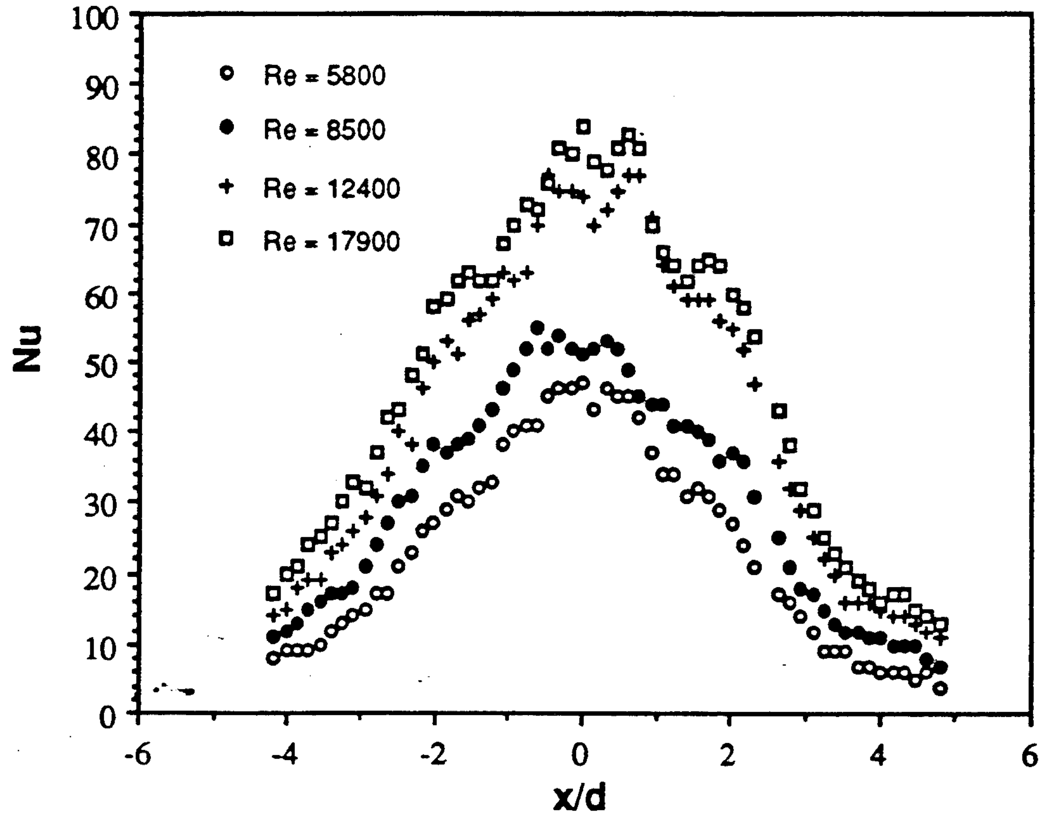



1 x1 pixel
2 x 2 pixels
3 x 3 pixels
4 x 4 pixels
5 x 5 pixels
Temperature (C)
radial position (mm)
pin contact
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
20.0
52
54
56
58
60

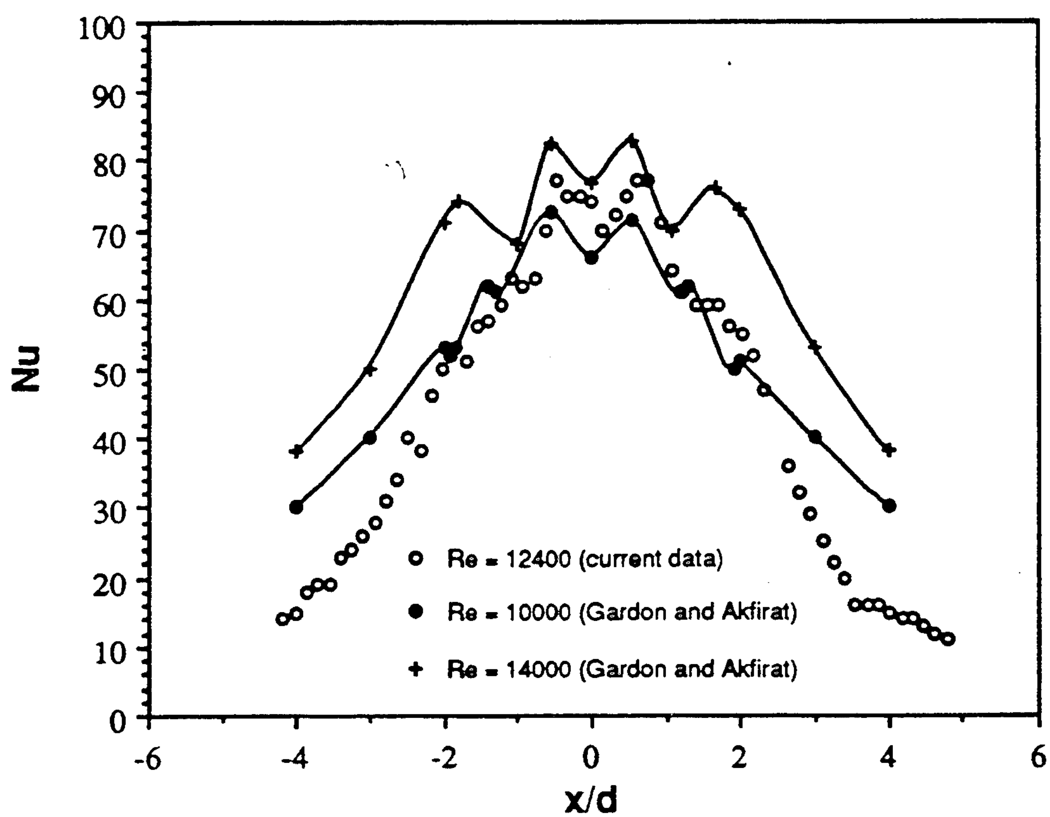

1 x 1 pixel
2 x 2 pixels
3 x 3 pixels
Temperature (C)
radial position (mm)
pin contact
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
20.0
52
54
56
58
60

Case 3: Jet Impingement Local Heat Transfer Measurement





Jet Impingement Local Nusselt Number Profiles



Recommendations

- Transient Measurement Capability
- Optical Heat Flux Development
- High-Temperature Measurement Capability

John Sullivan

School of Aeronautics and Astronautics
Purdue University

FLUORESCENT PAINTS

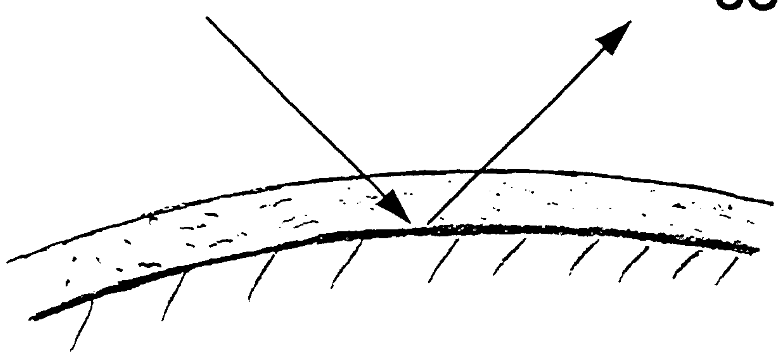
John Sullivan
School of Aeronautics and Astronautics
Purdue University

Fluorescent Paints

- Pressure
- Temperature
  - Heat Transfer
  - skin Friction

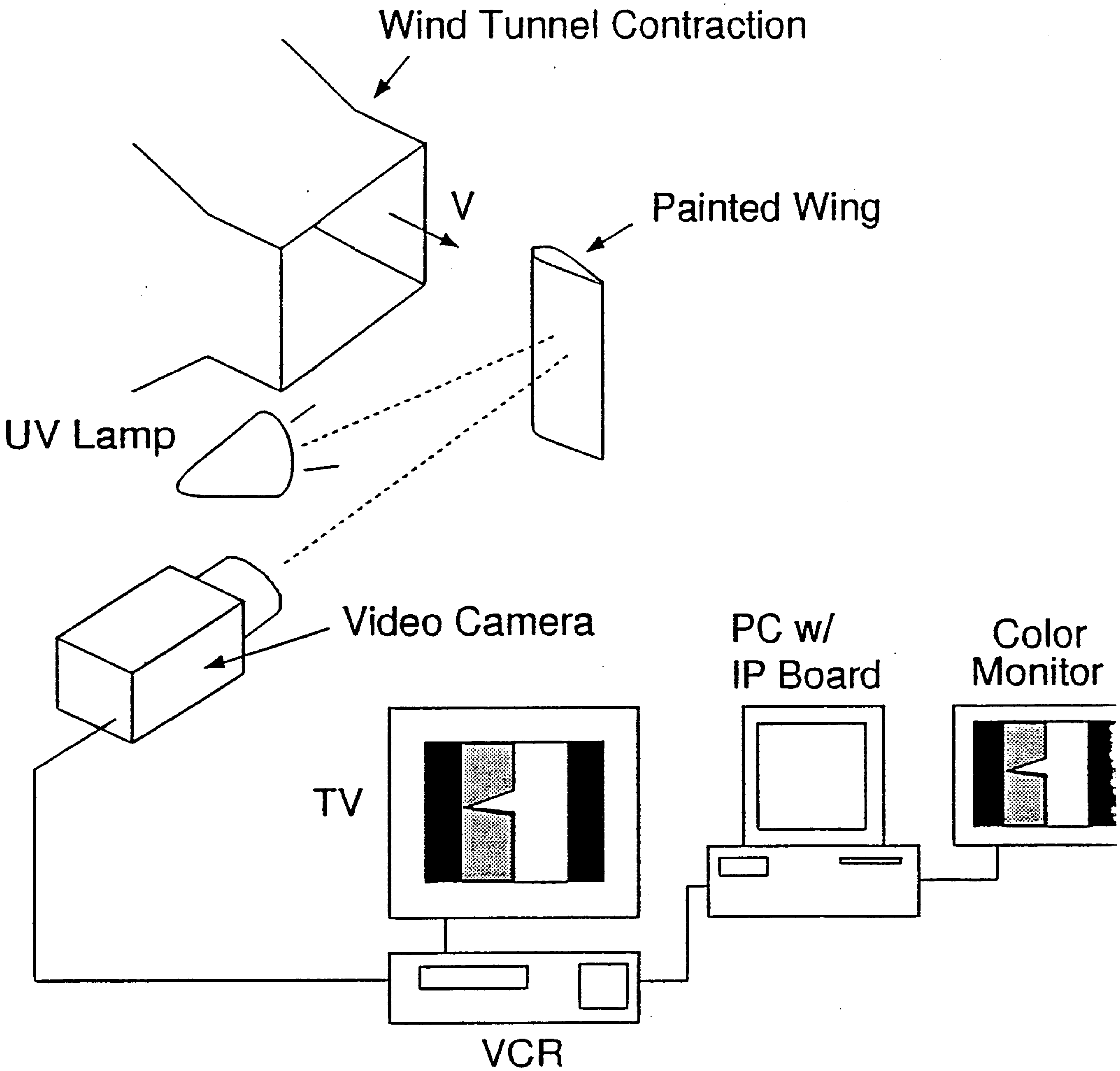
Incident Light
UV Lamp
Laser (SS or Pulsed)
Flash Lamp

Fluorescence
Detect with
CCD, PM, PD



Spatial Resolution
< 1 Micron
Time Response
1 KHz (Demonstrated)
>1 MHz (Theoretically)

Temperature Resolution
< .01 Deg. K
Pressure Resolution
< .01 Psi.



Steady-State Wing Transition Experiment

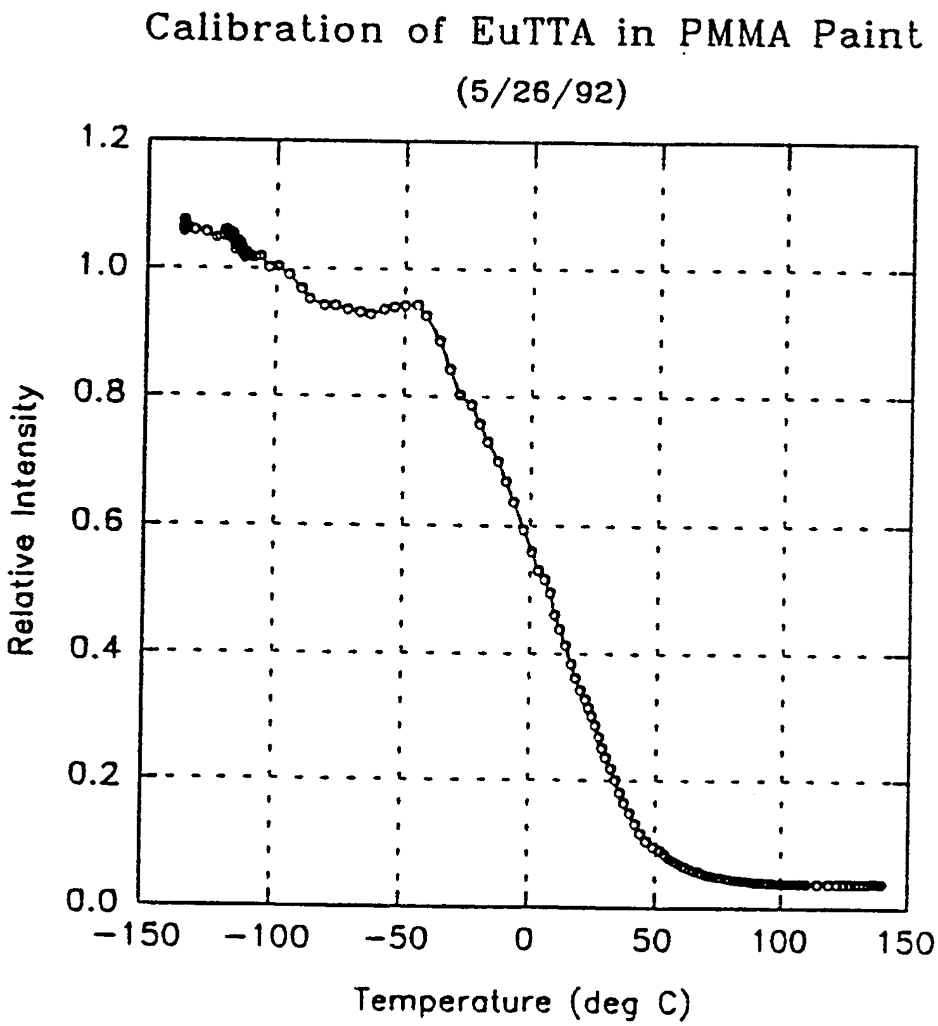
Paint Materials

Fluorophores:

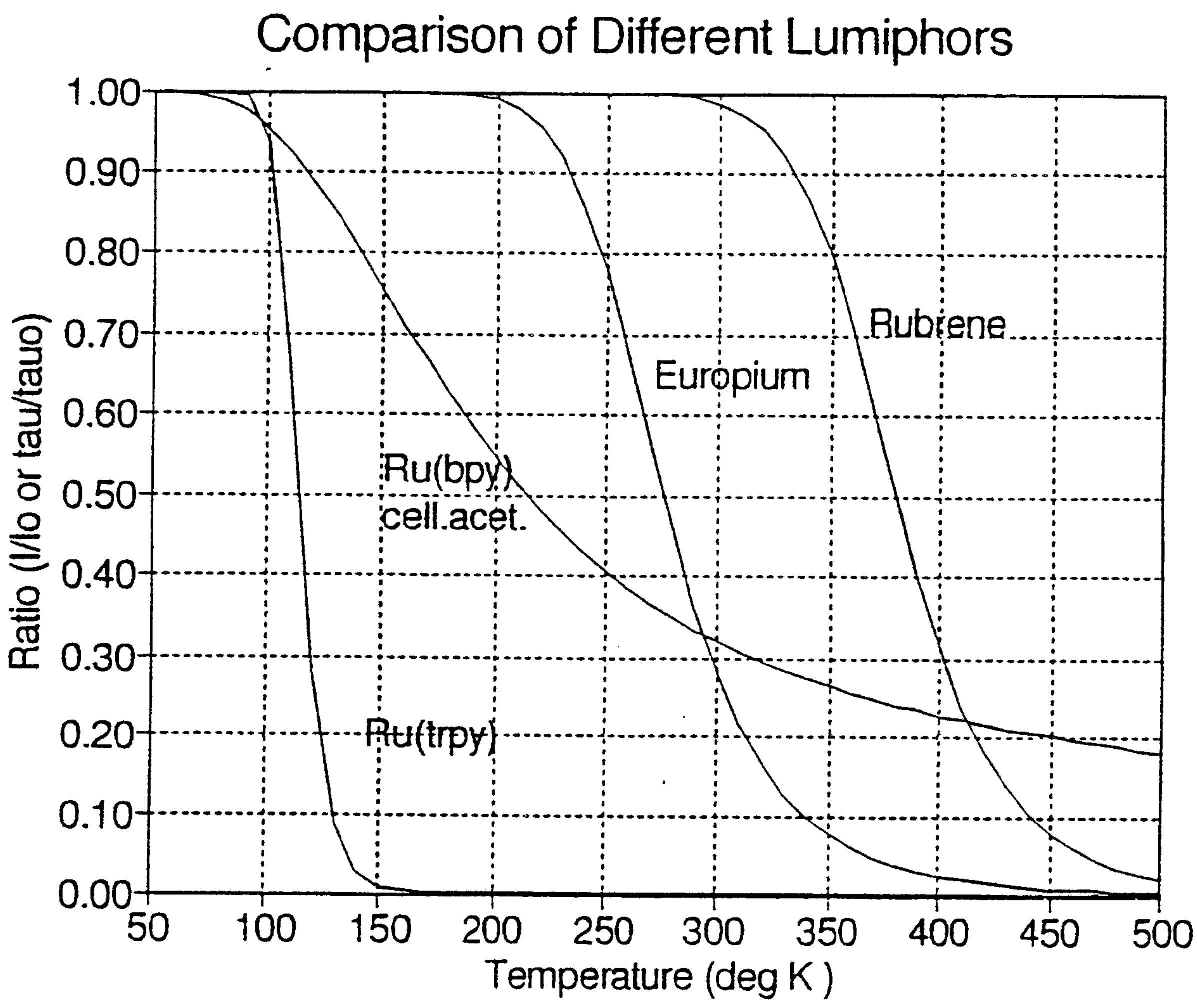
Rhodamine B, EuTTA, Ruth(bipy), Pyrene, Anthracene, PtOEP, Ruth(trpy), Pyronin Y, Pyronin B, Rubrene, Sulpharhodamine B, Perylenedicarboximide, Quinizarin, Coumarin, Erythrosin B, Rose Bengal

Matrices:

PMMA, Cellulose Acetate, Dope, PVC, Polyvinylpyrrolidone, Polystyrene, Polydimethylsiloxane, Polycarbonate, Sucrose Octaacetate, Ethyl Cellulose, Polyvinyl Acetate, Polyvinyl Alcohol



Calibration of EuTTA in PMMA Paint
(5/26/92)
Relative Intensity
Temperature (deg C)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−150
−100
−50
0
50
100
150


Comparison of Different Lumiphors
Ratio (I/Io or tau/tauo)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
50
100
150
200
250
300
350
400
450
500
Temperature (deg K)
Rubrene
Europium
Ru(bpy)
cell.acet.
Ru(trpy)

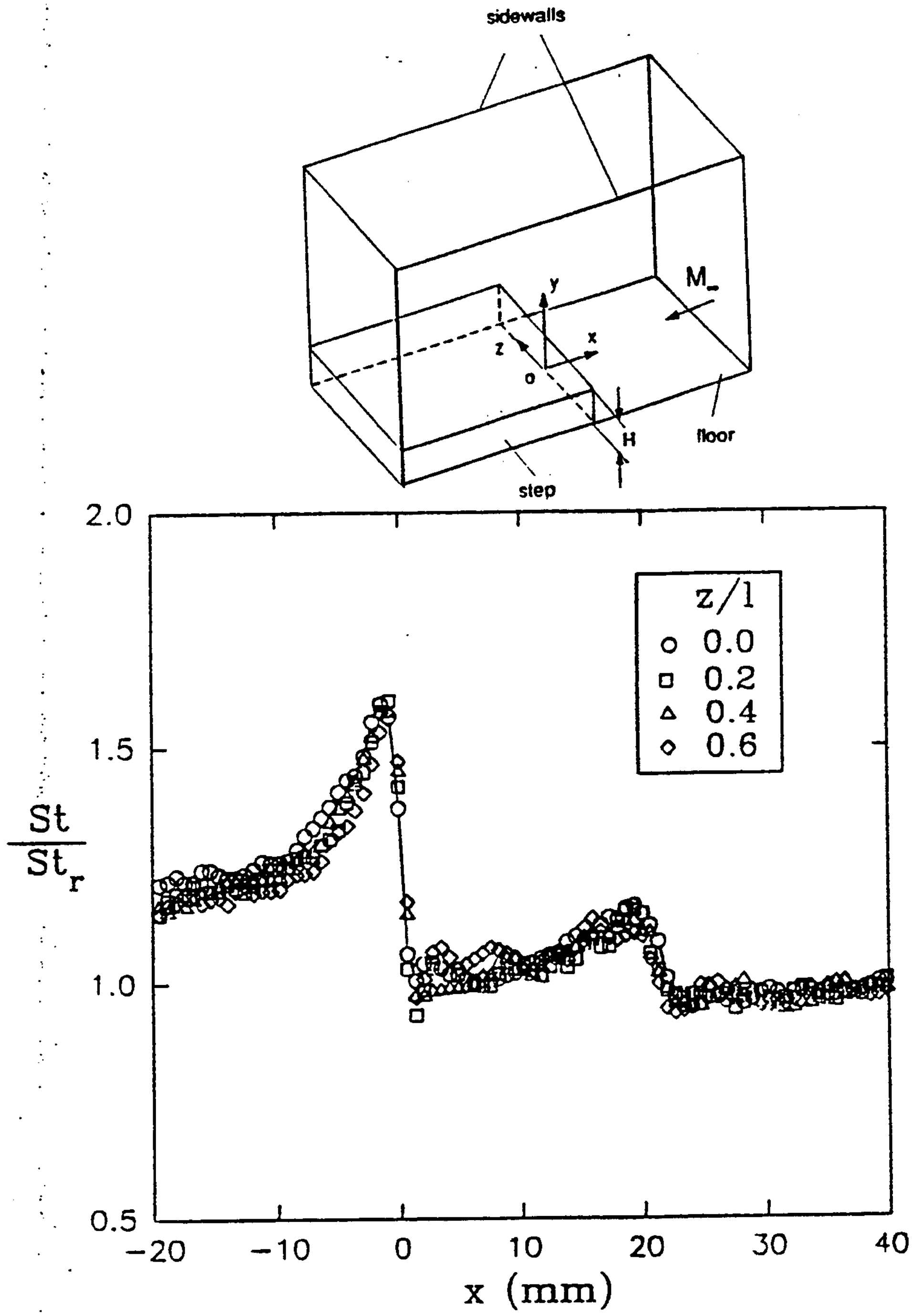


Fig. X Relative Stanton number distributions in the flow over a forward-facing step (3 mm)

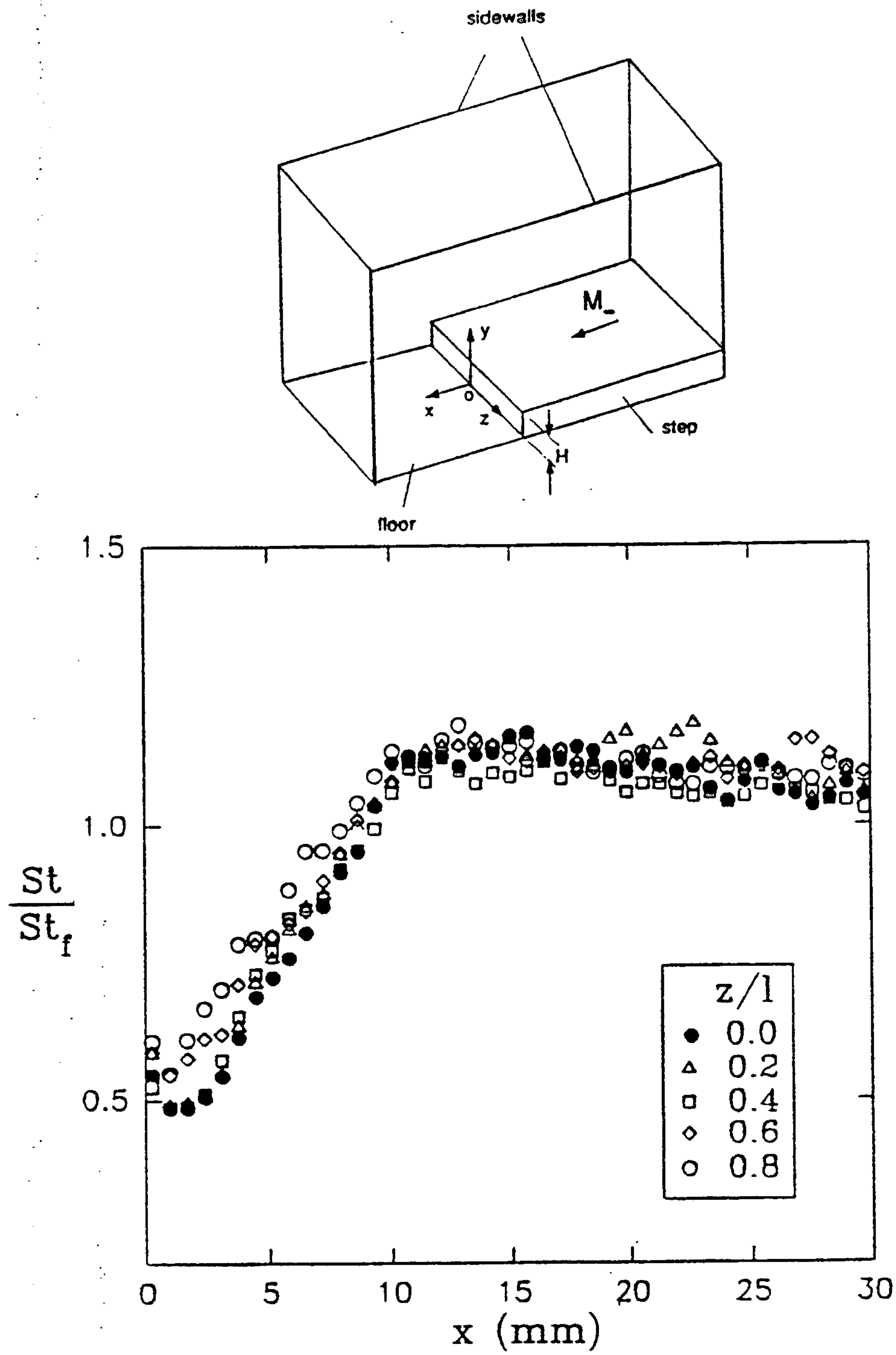


Fig. X Relative Stanton number distributions in the flow over a backward-facing step (3 mm)

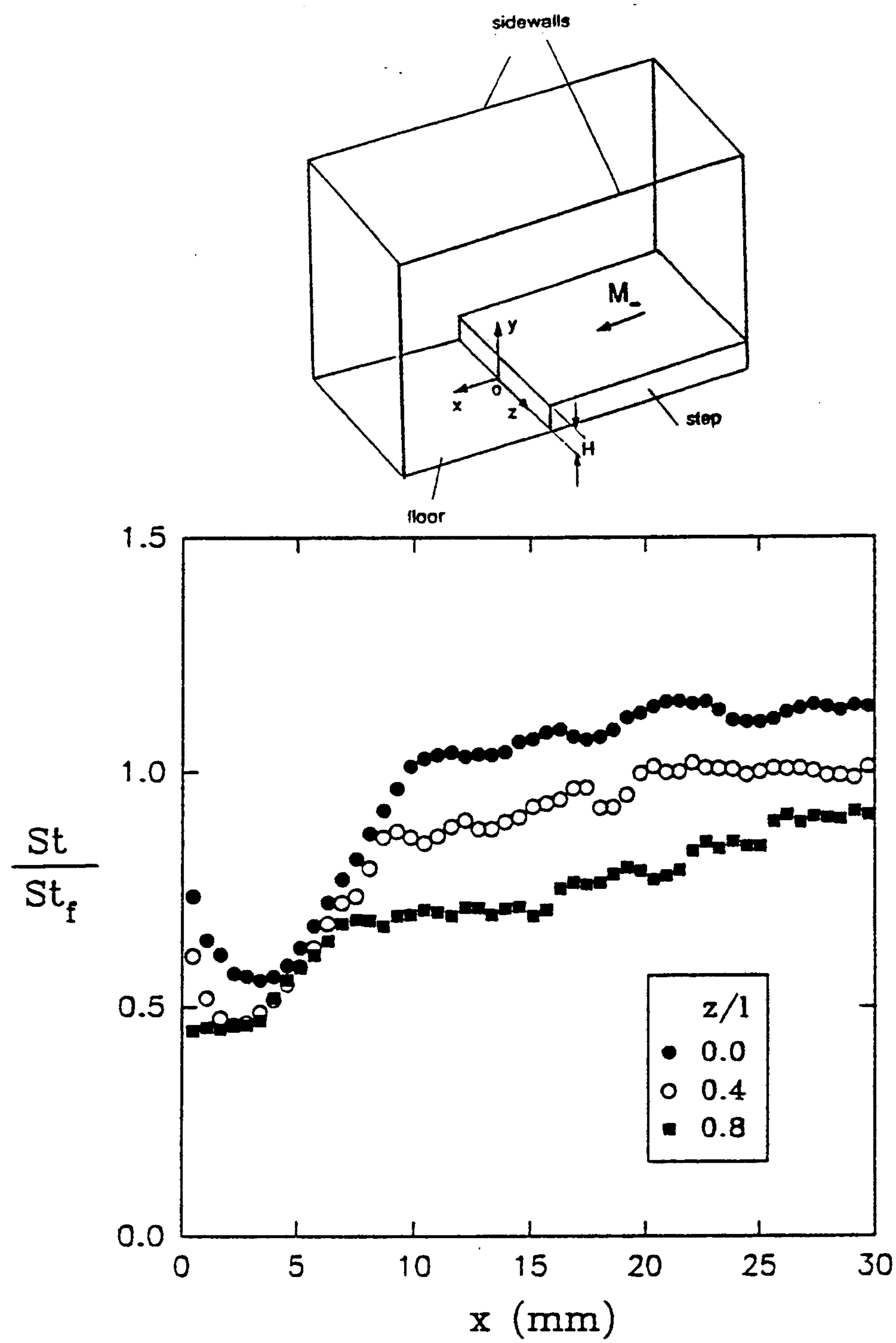


Fig. X Relative Stanton number distributions in the flow over a backward-facing step (6 mm)

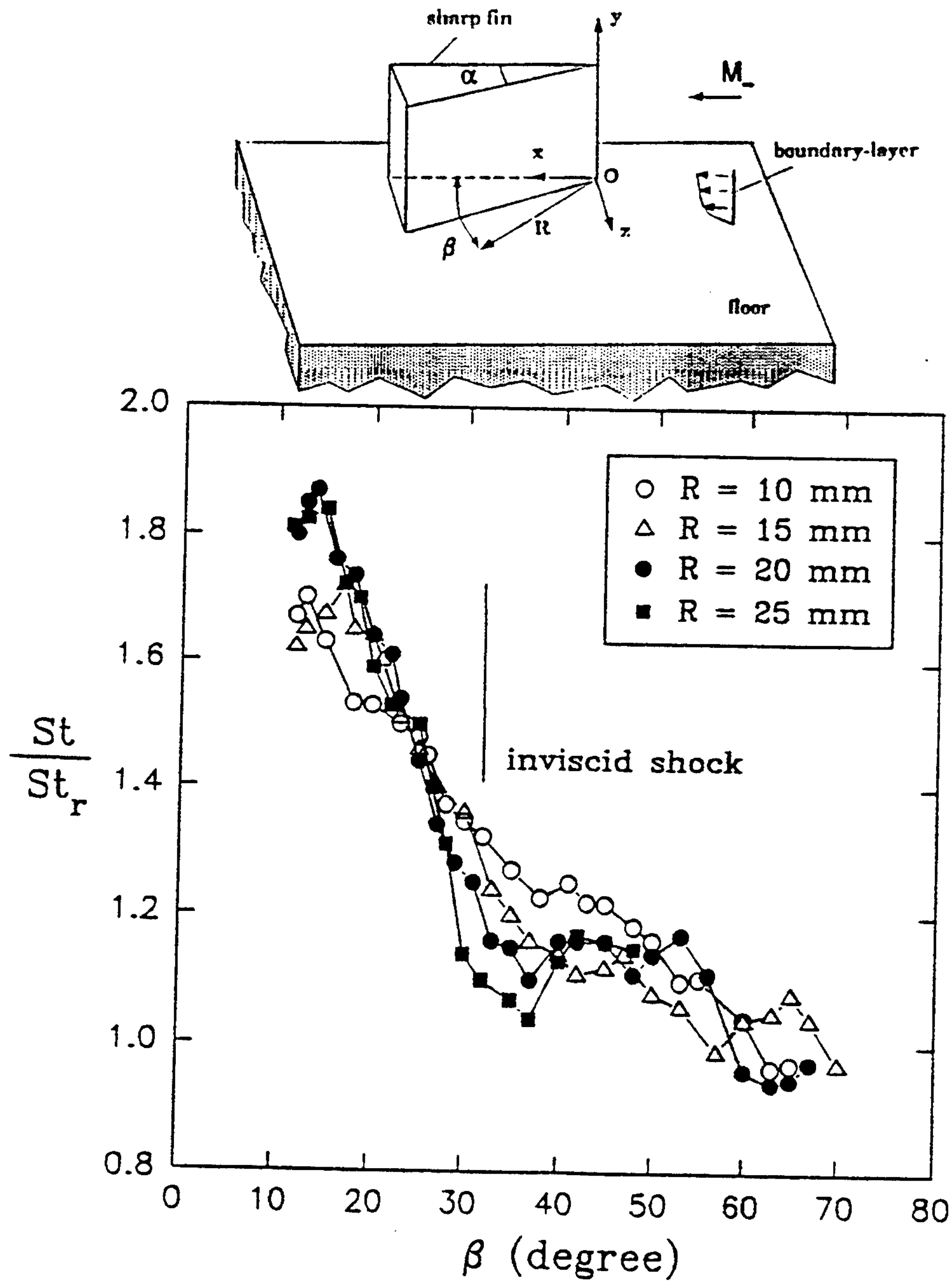


Fig. X Swept shock/boundary-layer interaction

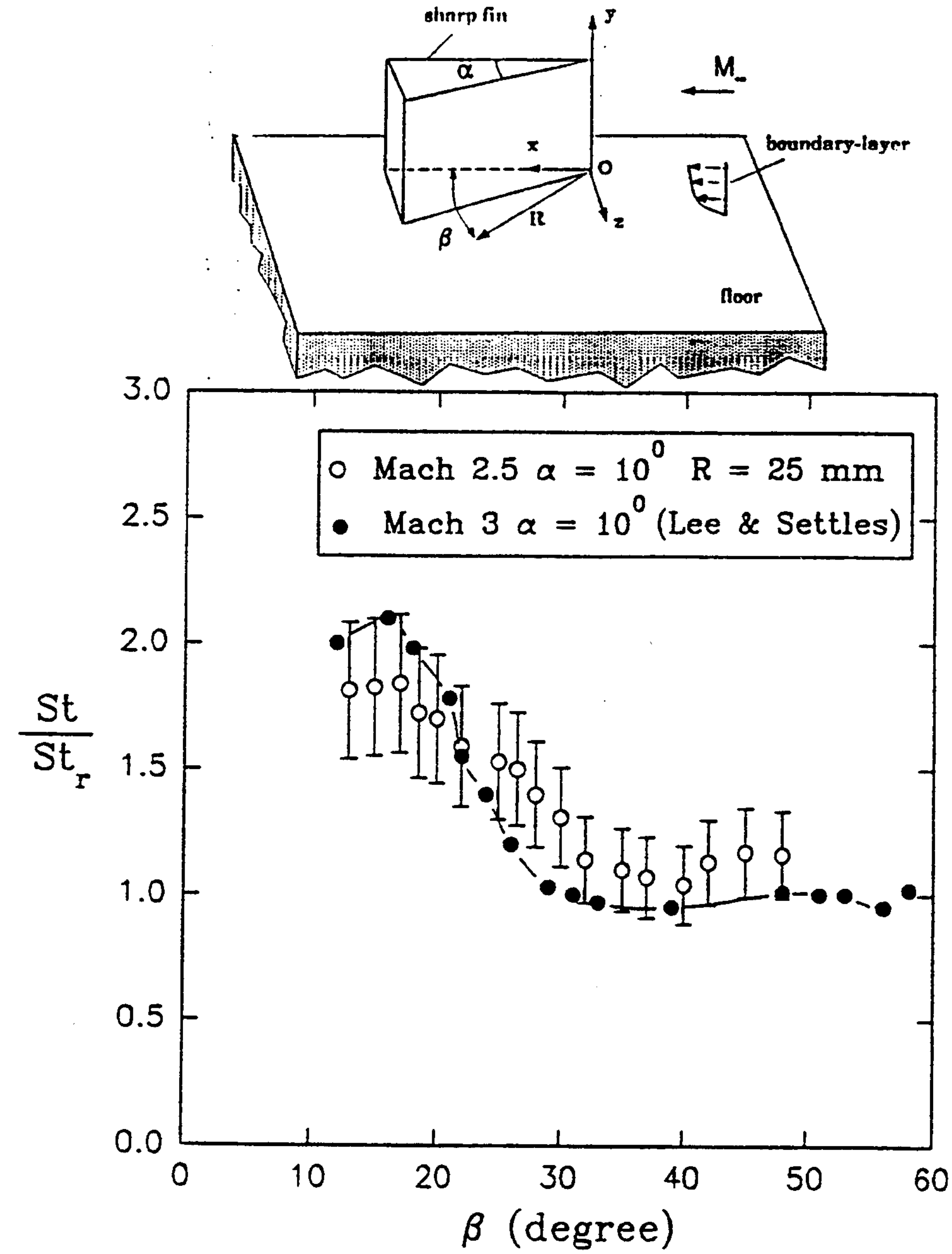


Fig. X Comparison with other measurements for swept shock/boundary-layer interaction

COMPRESSOR STABILITY
ROTATING STALL AND SURGE

by

Professor A.H. Epstein
Gas Turbine Laboratory
Massachusetts Institute of Technology
Cambridge, MA 02139

Presented at

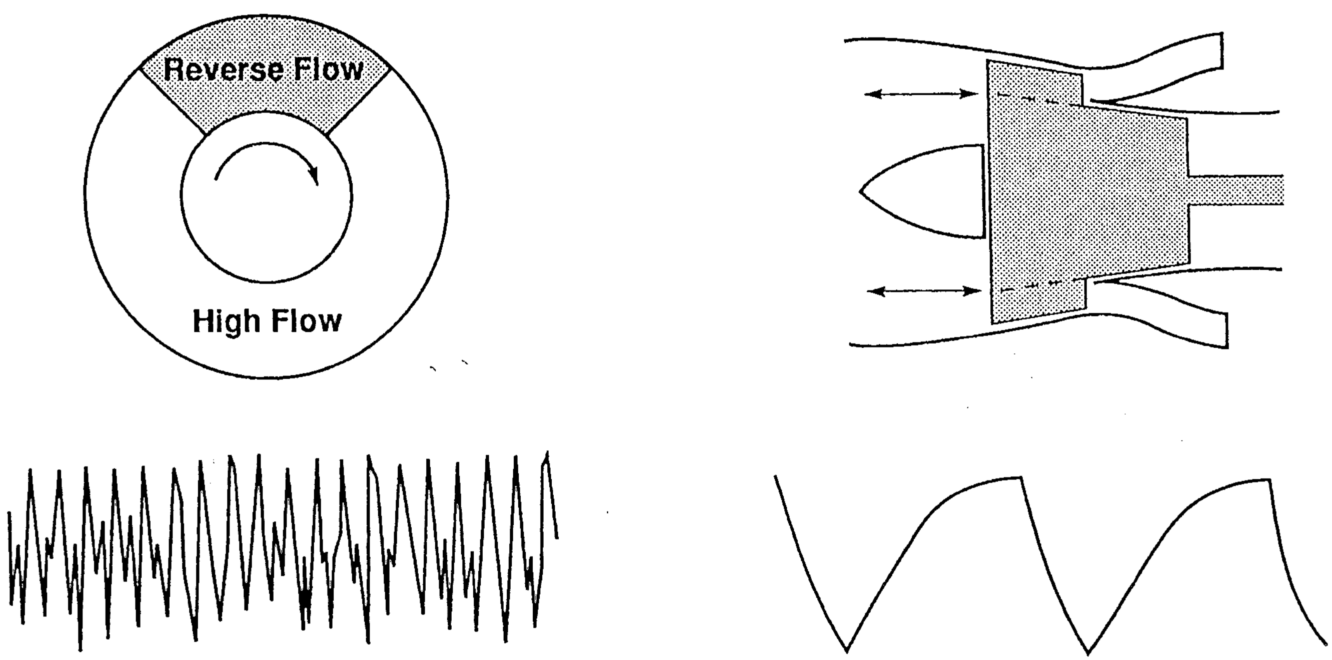
WINCAT

October 1993

COMPRESSOR FLOW INSTABILITIES

Rotating Stall
Circumferentially Nonuniform Flow

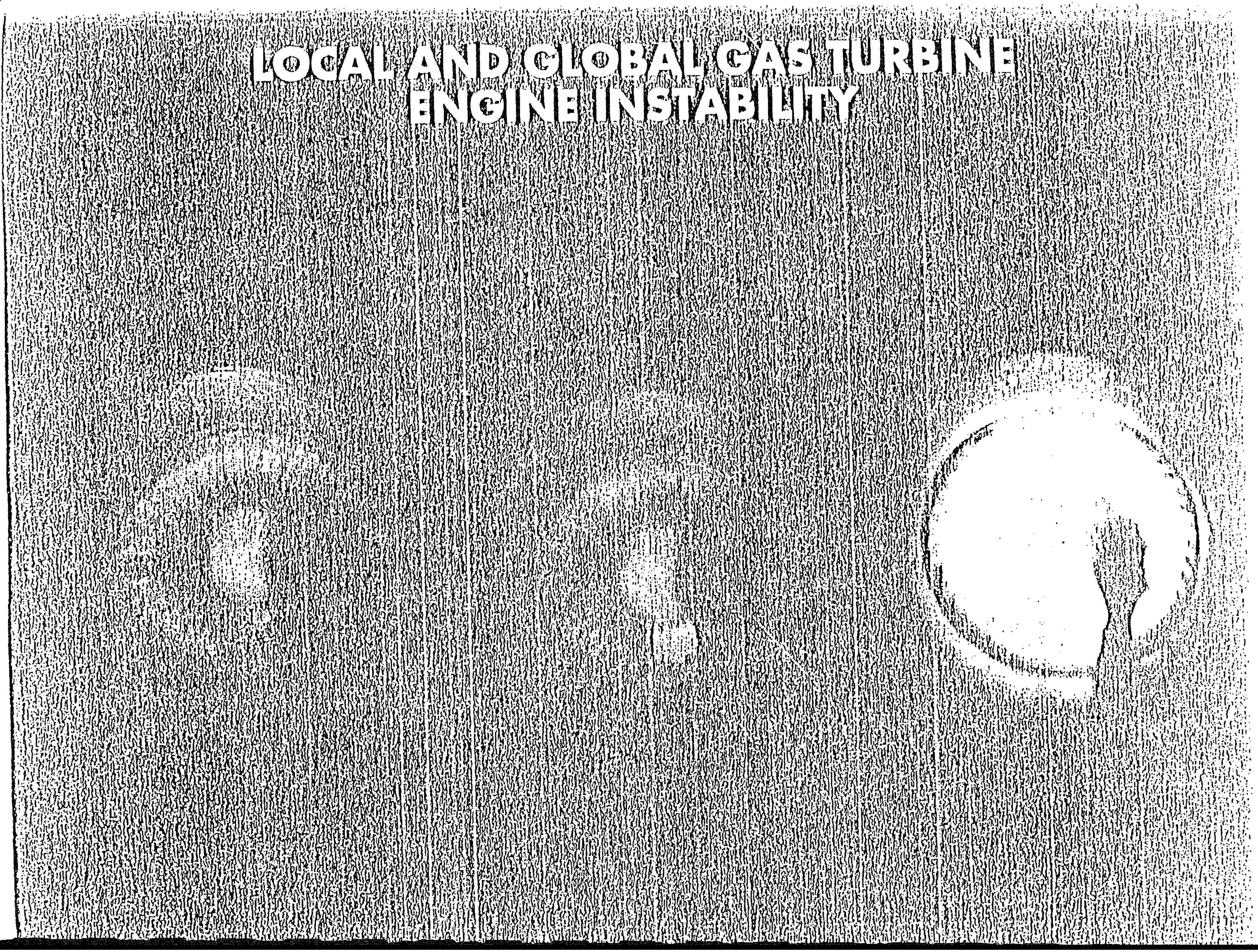
Surge
Axially Oscillating Flow



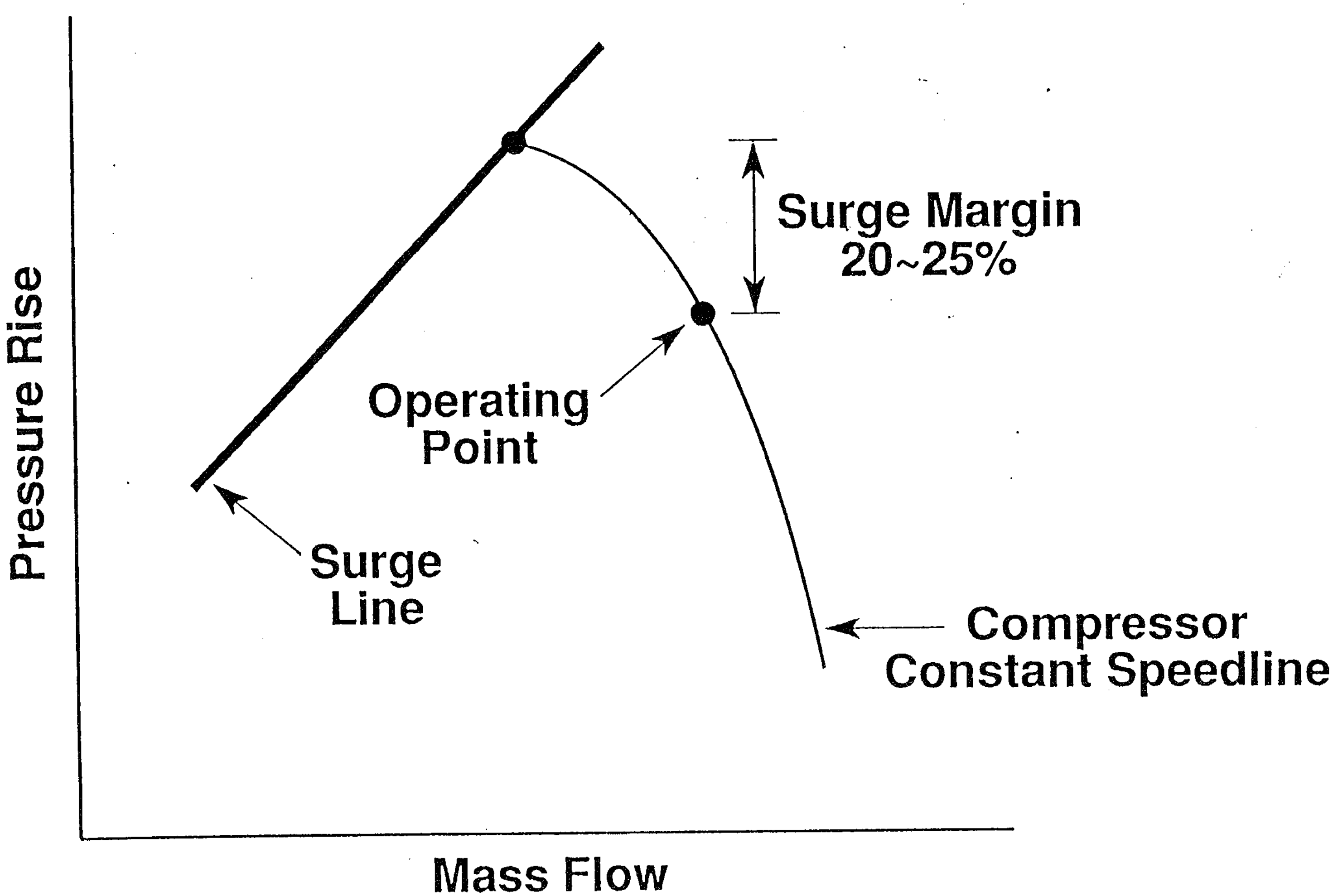
Frequency ~ 50-100 Hz

Frequency ~ 3-10 Hz

LOCAL AND GLOBAL GAS TURBINE ENGINE INSTABILITY



COMPRESSOR OPERATING CHARACTERISTIC



WHY ARE COMPRESSOR INSTABILITIES IMPORTANT?

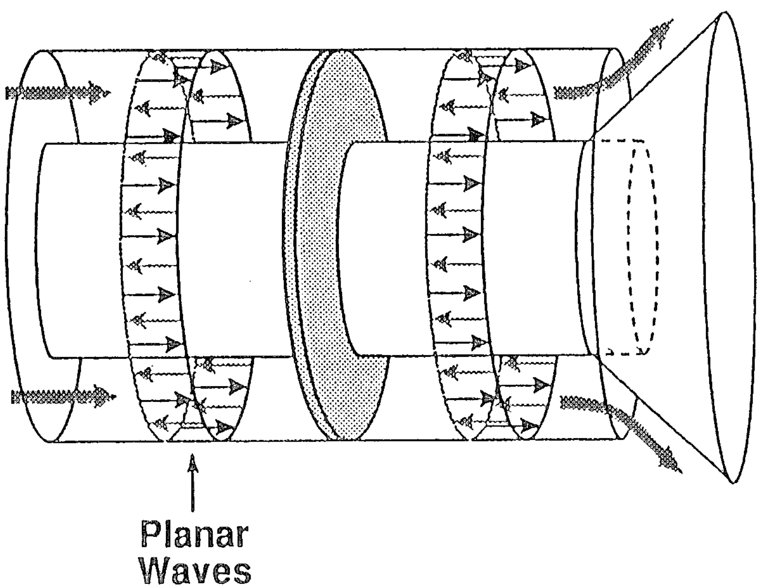
- Safety (surge) margin costs 20-25% in compressor performance
- Surge is a limiting load for compressor mechanical design
- Surge and stall limit design space
- Instability limits now very difficult to predict
  - Can lead to expensive surprises during development
  - Sensitive to small geometric variations
- Engineering to accommodate instabilities increases aircraft gross takeoff weight by ~10%

ONE HISTORICAL VIEW OF COMPRESSOR INSTABILITIES

	Problems	Inventions	Theories
1940	Whittle Engine (Surge)	Bleed	
1950	J-79 (Surge)	Multiple Spools Variable Geometry	Emmons (Basic Concepts) Marble (Linear Theory)
1960	TF-30 (Surge)		
1970	JT9D (Rotating Stall)	Casing Treatment	Ploude (Distortion)
1980	F-100 (Nonrecoverable Stall)		Greitzer (Surge) Moore & Greitzer (Rotating Stall)
		Active Control(?)	

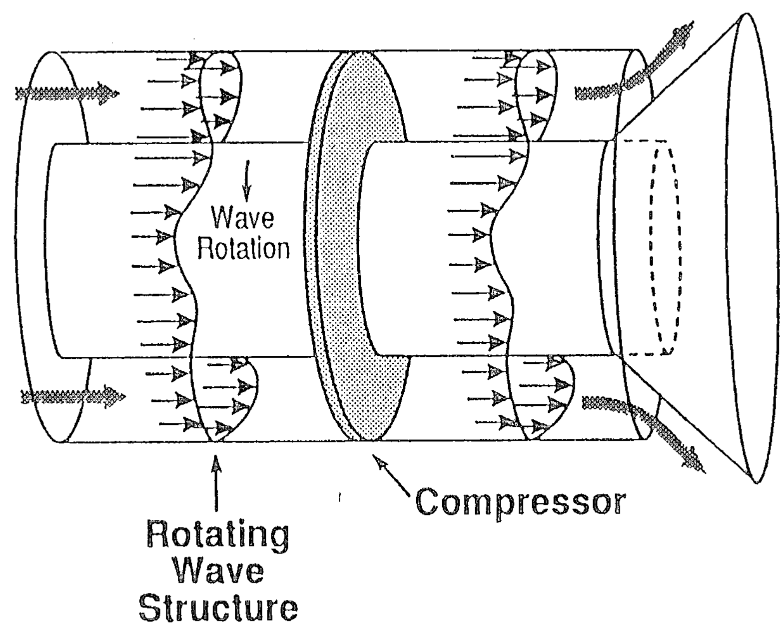
NATURAL OSCILLATORY MODES OF COMPRESSORS

Lowest Order



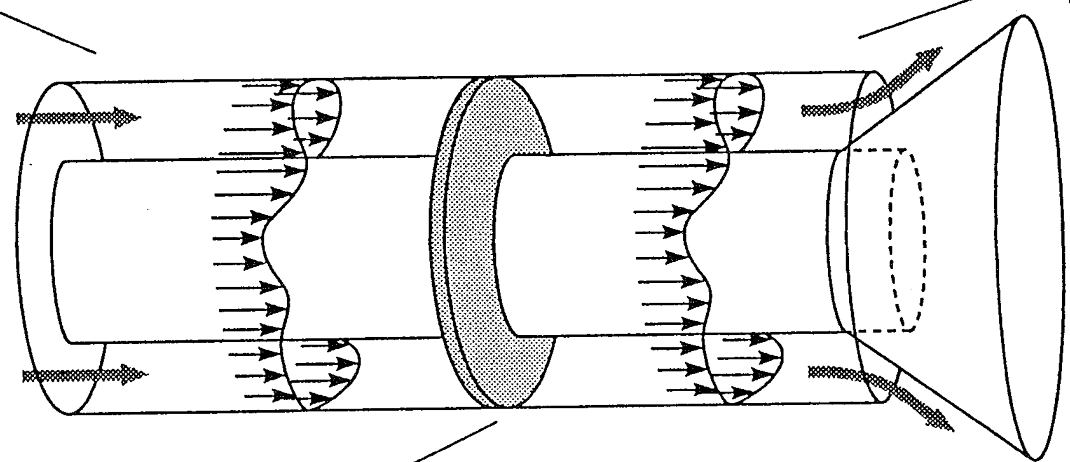
Surge

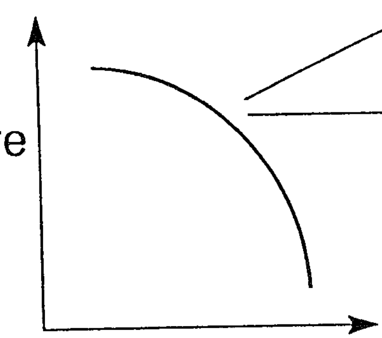
Higher Order



Rotating Stall

STABILITY MODEL OF FLOW IN COMPRESSION SYSTEM
(From Moore & Greitzer)



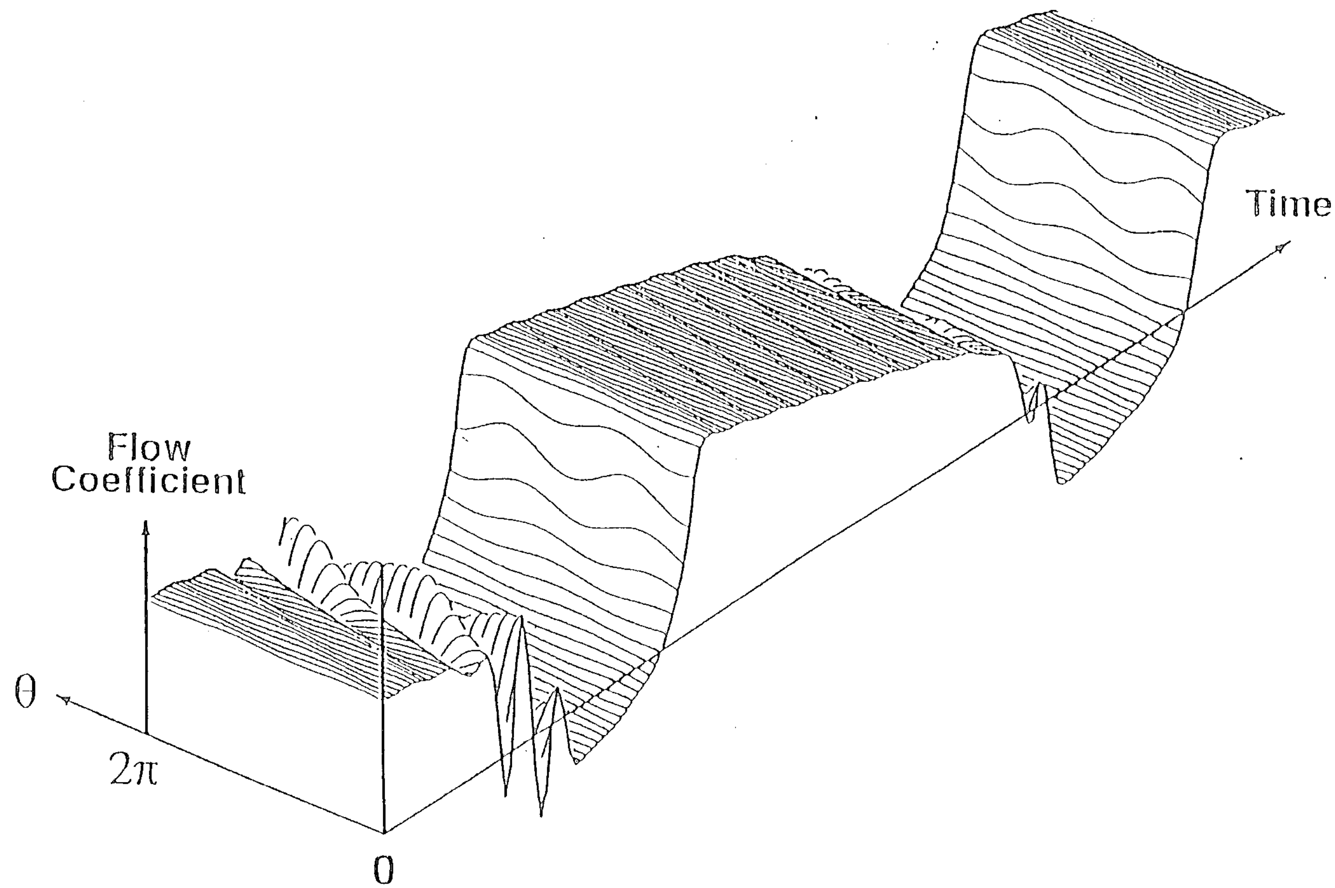


$$\Delta P = \left(\frac{\partial\psi}{\partial\phi}\right)\delta\phi - \delta L - (\mu)\frac{\partial(\delta\phi)}{\partial\tau} - (\lambda\omega_{rotor})\frac{\partial(\delta\phi)}{\partial\theta}$$

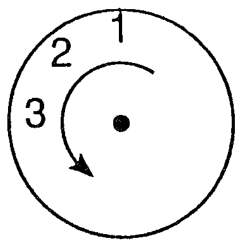
$\mu, \lambda \equiv$ Fluid Inertia (from geometry)
$\delta L \equiv$ Blade Row Losses (time lag)

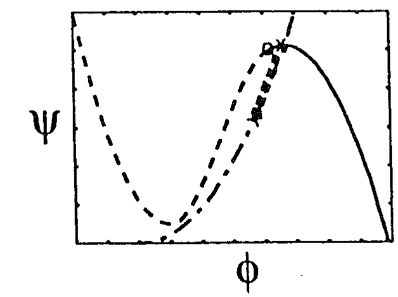
HYDRODYNAMIC STABILITY MODEL PREDICTS WAVE PATTERN

- Small Amplitude Waves Travel About Circumference Prior to Instability -

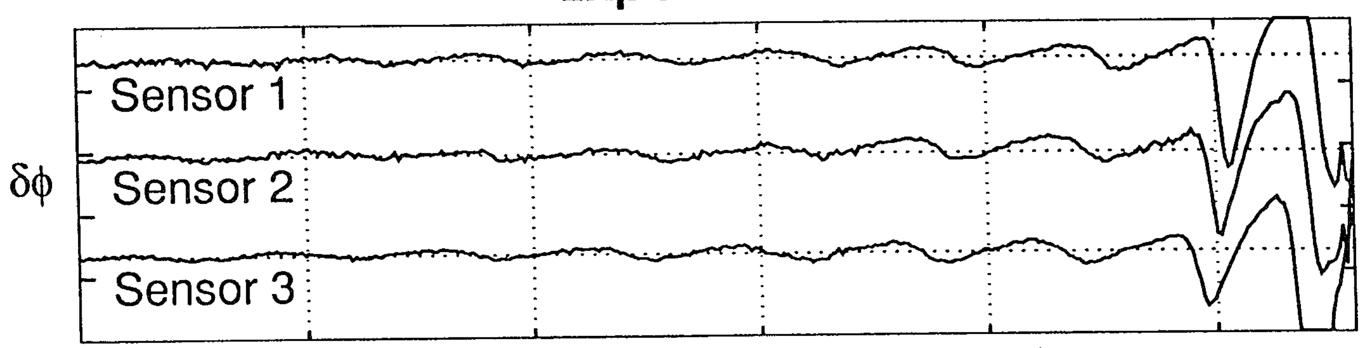


STALL INCEPTION IN MIT 3-STAGE COMPRESSOR

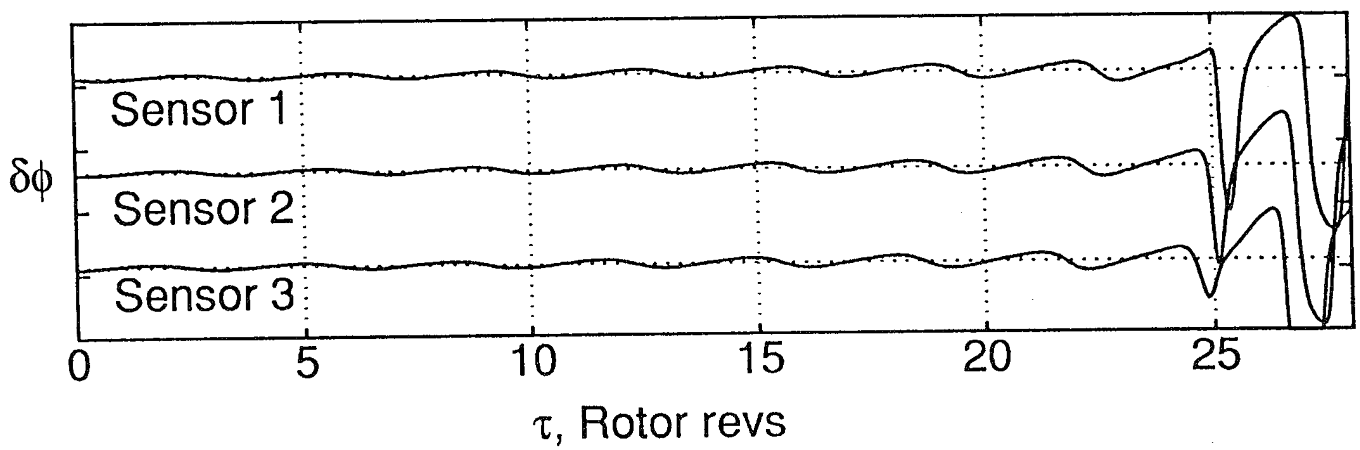




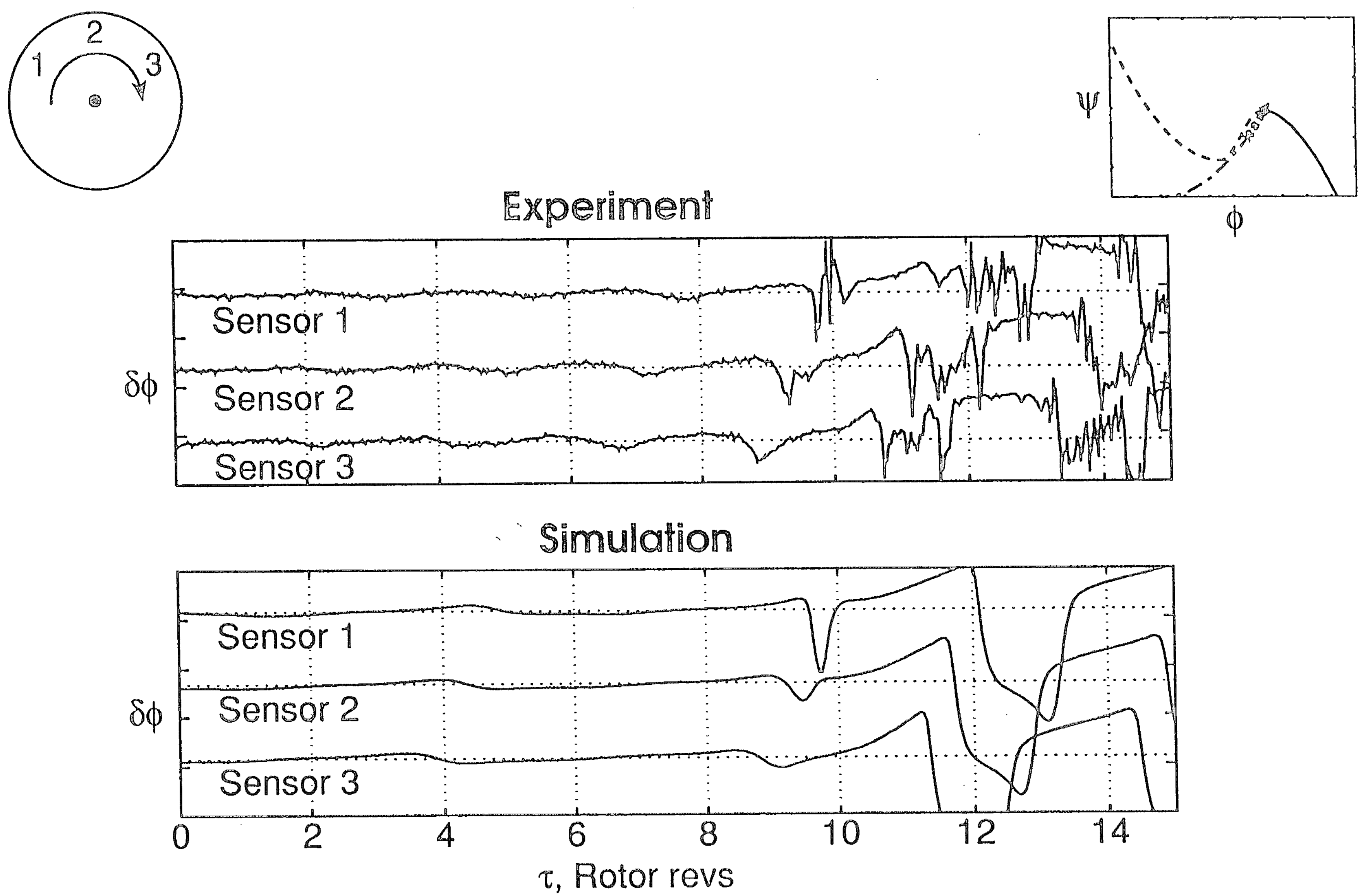
Experiment



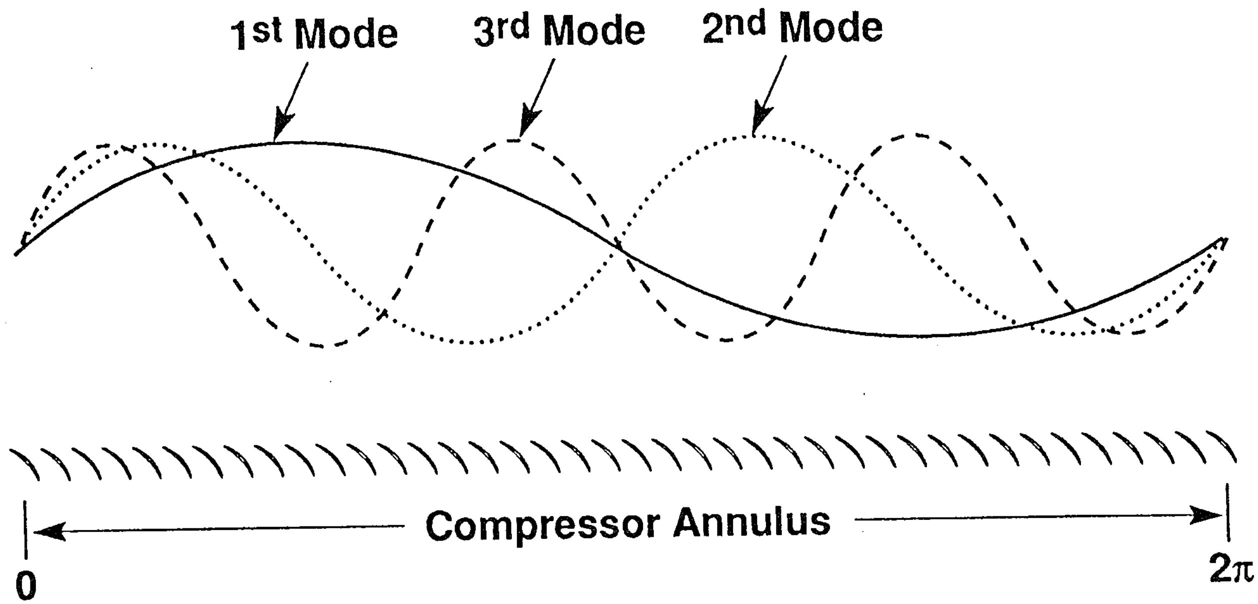
Non-Linear Simulation



STALL INCEPTION IN WHITTLE LAB 1-STAGE COMPRESSOR

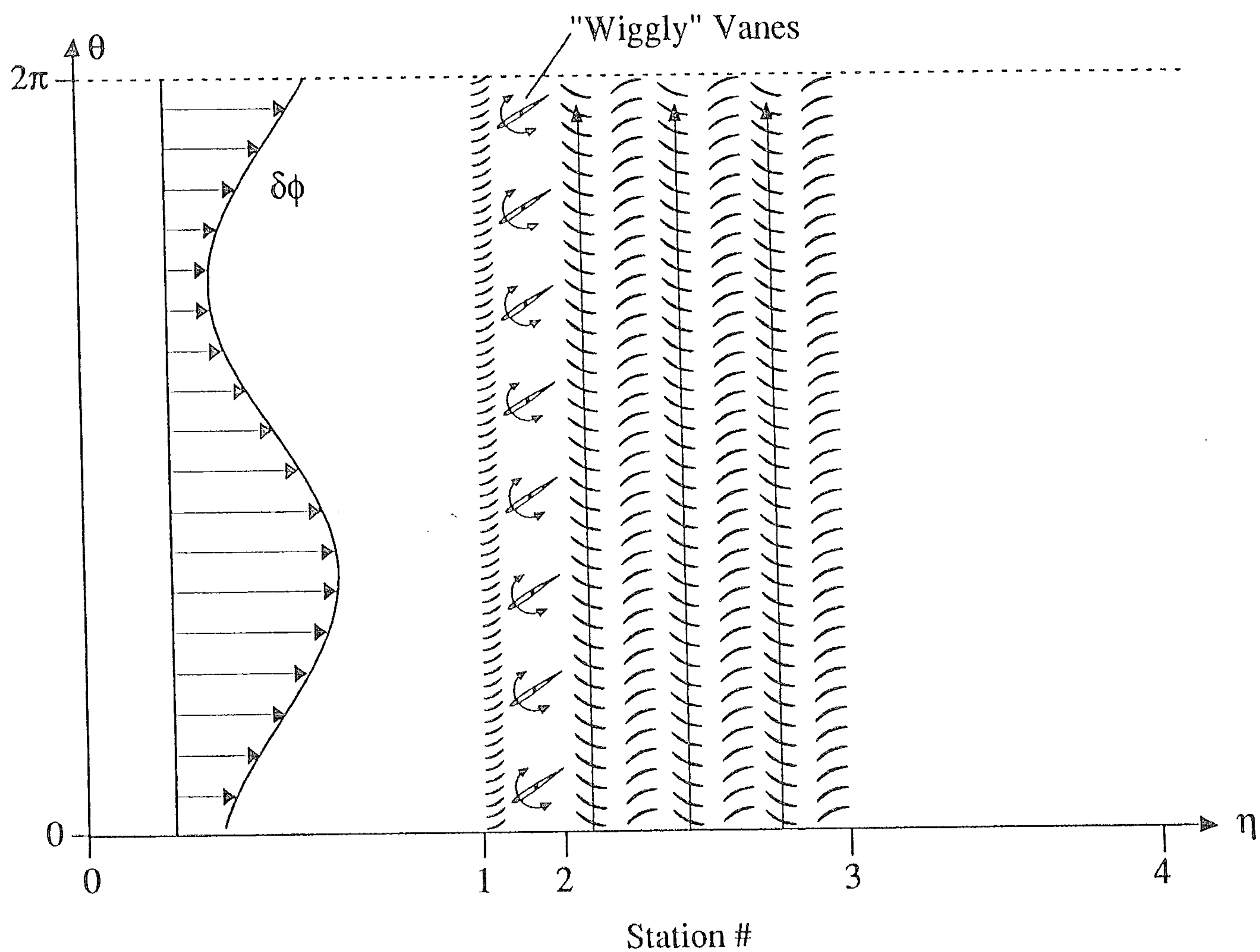


ANALYZING AND DETECTING ROTATING STALL

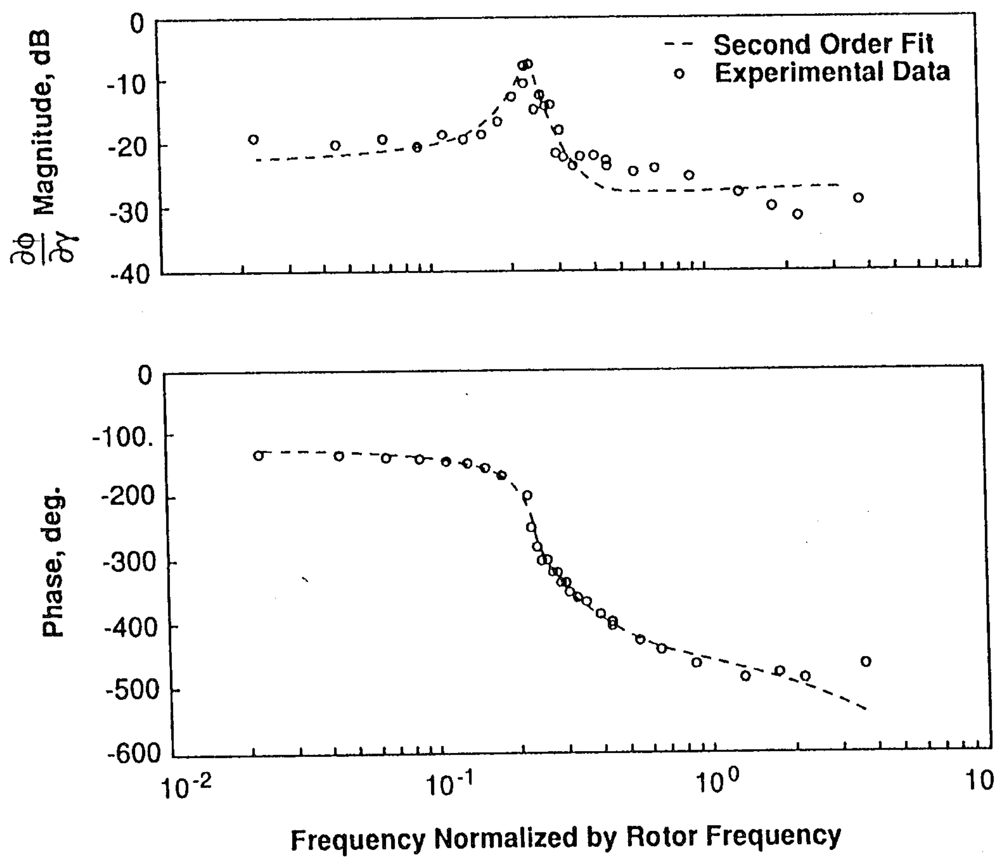


- Look for rotating waves
- Decompose into spatial Fourier modes
- Treat each mode individually
  - Detect mode by mode
  - Excite mode by mode

THREE-STAGE FORCED RESPONSE COMPRESSOR RIG



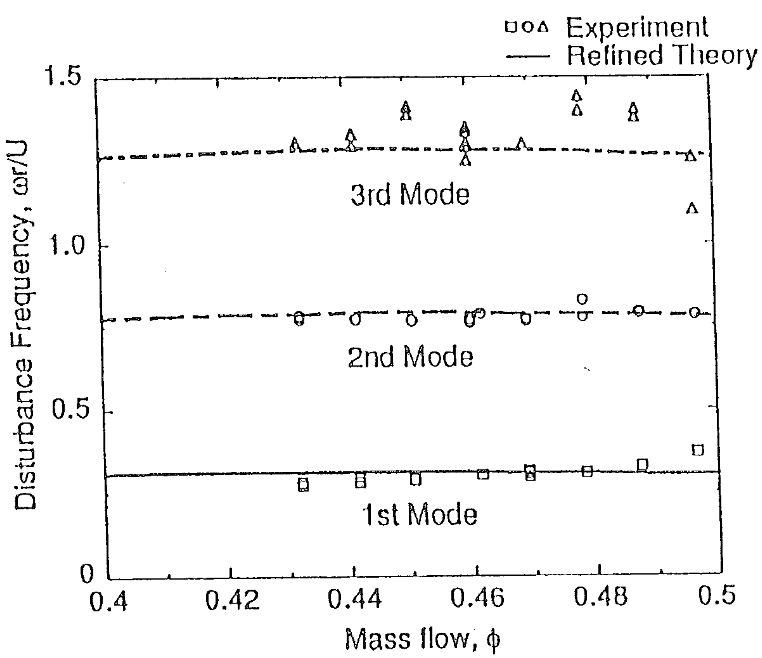
SINE WAVE RESPONSE OF COMPRESSOR
(Response to ±5° Vane Motion, γ)



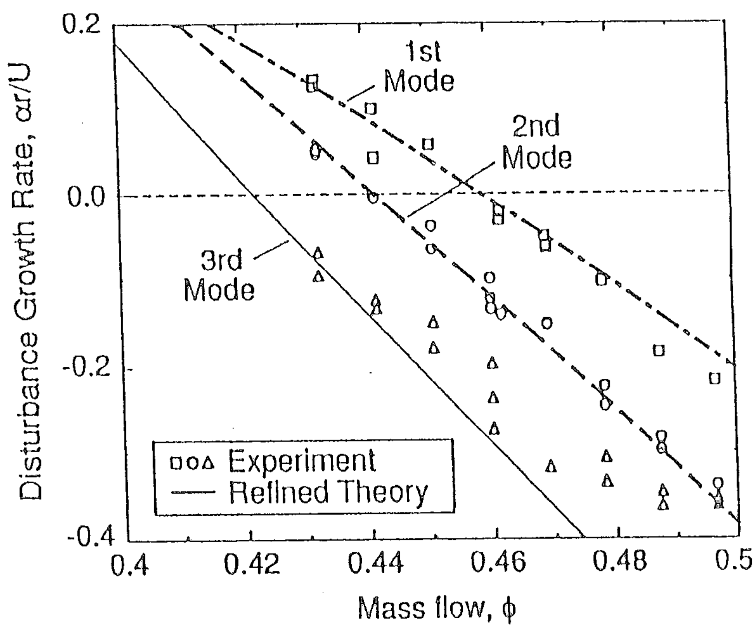
- Model form fits data very well

REFINED THEORY MATCHES DATA

Wave Speed

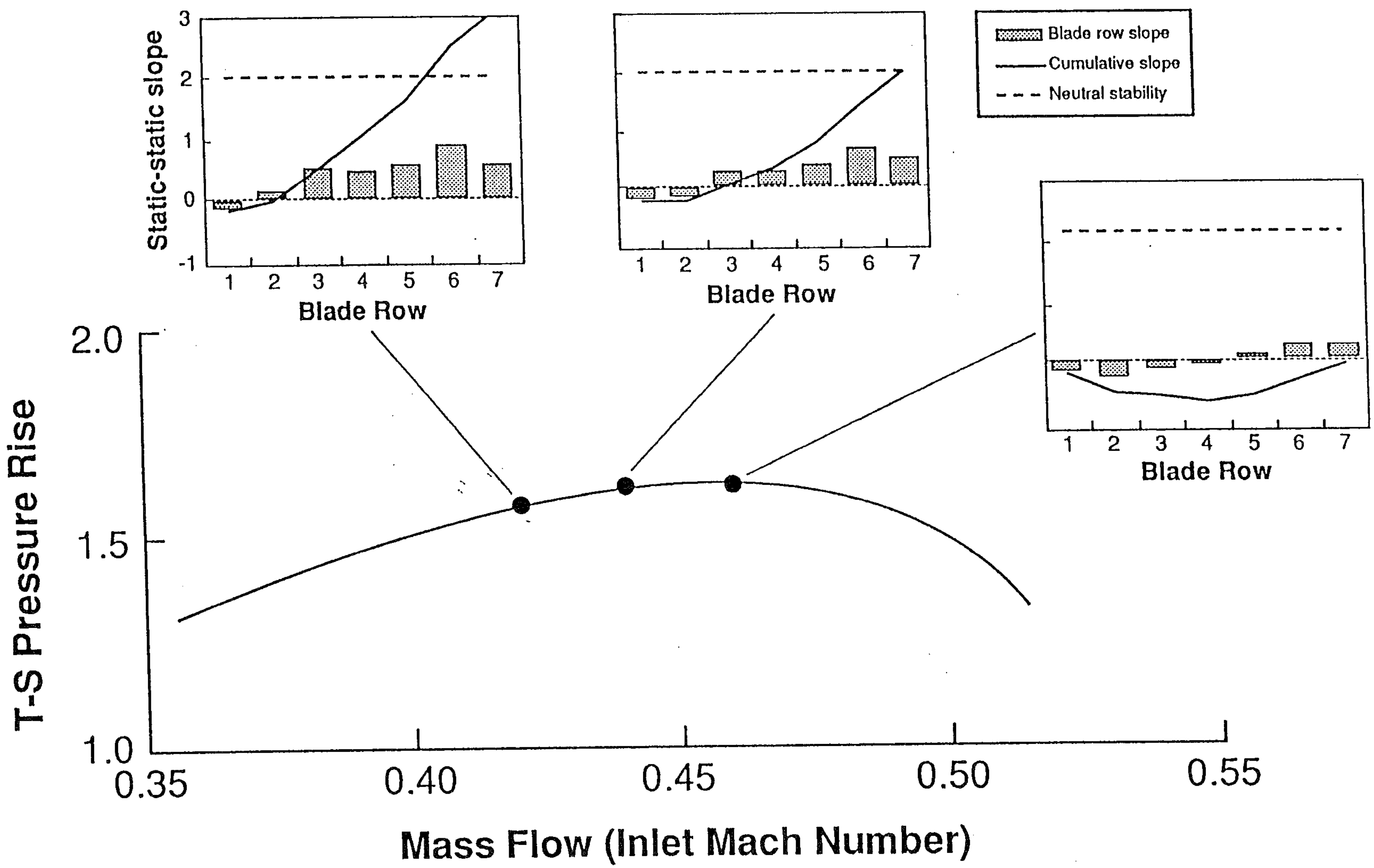


Wave Damping

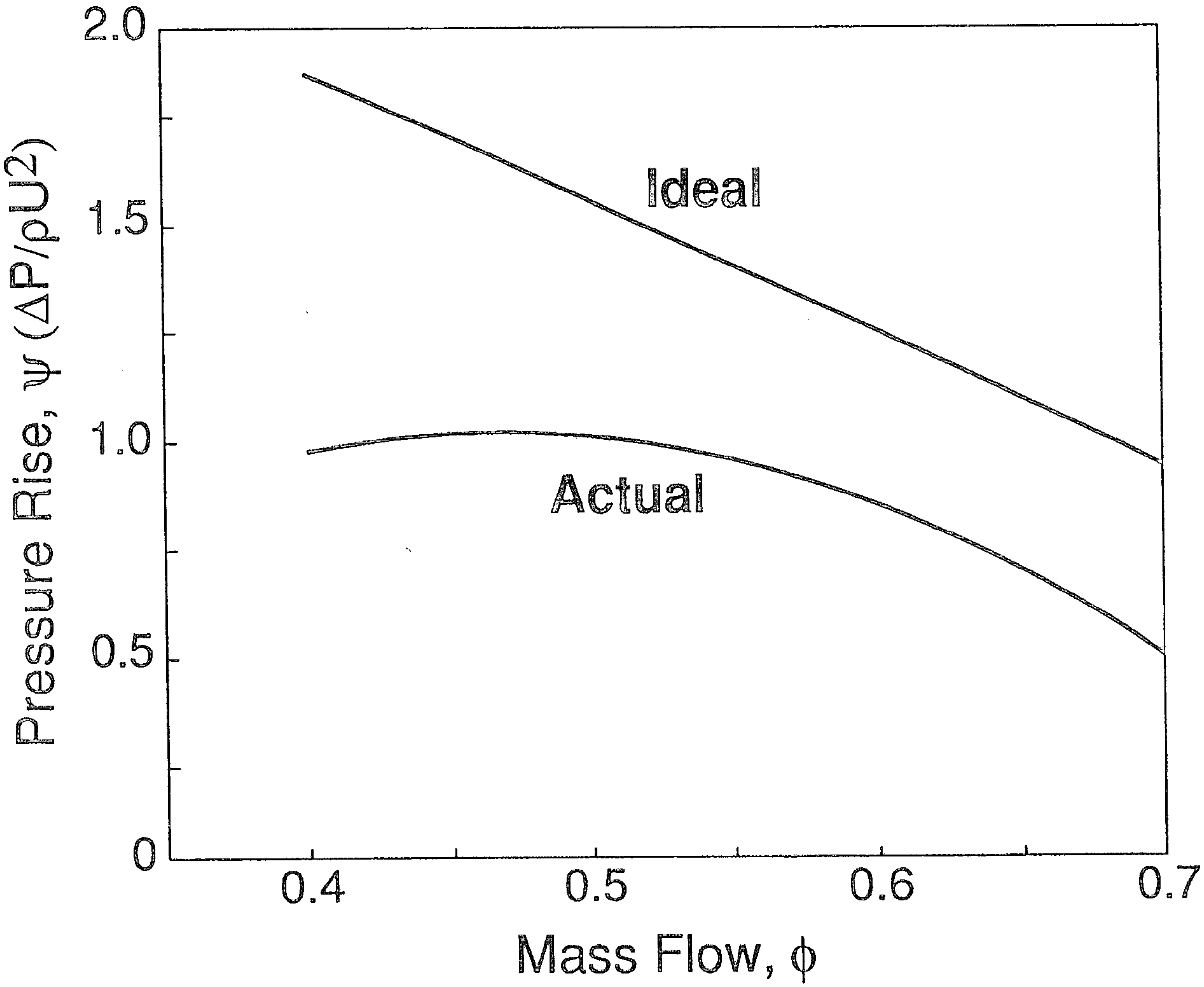


COMPRESSOR STABILITY SET BY BLADE ROW SLOPES

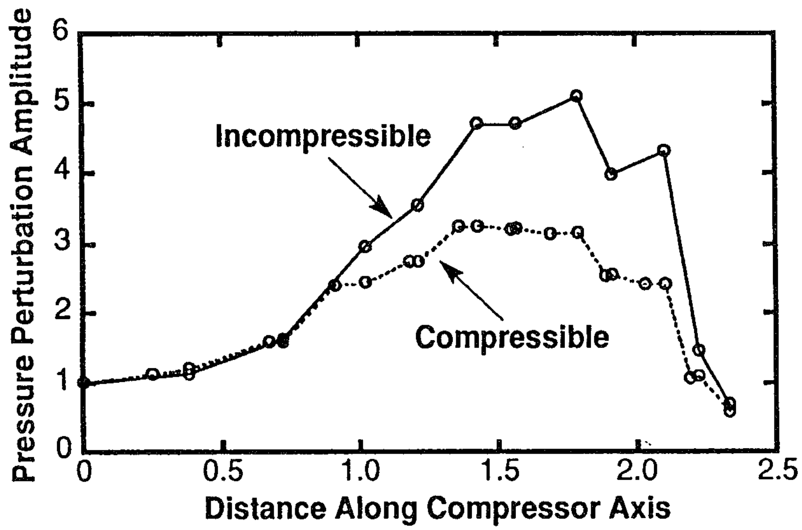
(Three-Stage, High Speed Compressor)



SPEEDLINE SLOPE DETERMINES COMPRESSOR STABILITY
- Slope Set By Losses and Deviation -



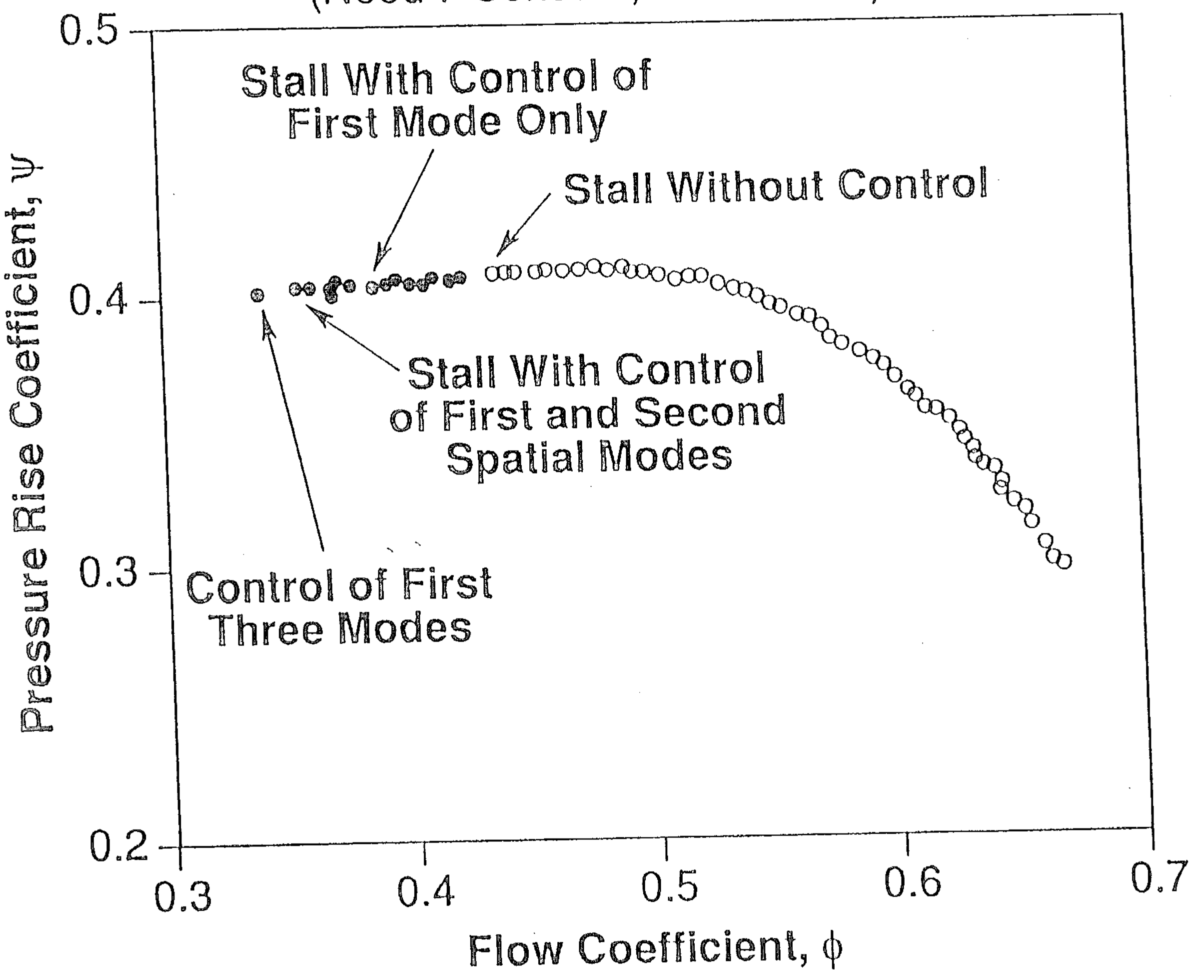
ROTATING STALL IS A GLOBAL INSTABILITY



- For well-matched compressors
  - Behavior qualitatively similar to low speed compressors
  - Instability is global, not local to individual blade rows
  - These findings at odds with conventional "wisdom"
- Speedline slope sets instability boundary

CONTROL OF FIRST THREE MODES EXTENDS RANGE BY 25%

(Need 7 Sensors, 7 Actuators)



SUMMARY OF RESEARCH FINDINGS TO DATE

- Rotating stall preceeds surge
- Rotating stall is preceeded by low amplitude rotating disturbances
  - Long length scale waves predicted by 2-D theory
  - Short length scale disturbances which may represent 3-D instability modes
- Hydrodynamic stability theory is very useful
- Damping precursor disturbances prevents surge and stall
- The compressor as a <u>whole</u> goes unstable
  - Disturbance not necessarily strongest in heaviest loaded stages
- Distortion is a major driver of instability
- Compressor <u>slope</u> is the most important determinant of stability

COMPRESSOR STABILITY DESIGN TECHNOLOGY REQUIREMENTS

- Accurate methods for predicting stability boundaries
- Quantitative connection between geometry and instability
- Compressor designs with improved stability characteristics
  - Less sensitivity to small geometry changes (especially tip clearance)
  - Less sensitivity to static and dynamic distortion
  - Increased stable operating range
    1) Active control
    2) Structural dynamic control
    3) New design space insights
    4) ?

CURRENT (OPTIMISTIC) STATE OF THE ART ASSESSMENT

- Prediction
  - Given compressor slope, stability boundary can be estimated for high hub-to-tip ratio (i.e., 2-D) compressors
- Range increase
  - Active control can increase stable operating range significantly
  - So can structural dynamic control
- Problems
  - How do we predict the compressor slopes adequately?
  - What about 3-D compressors?
  - Quantitative tools for distortion evaluation

FRUITFUL RESEARCH AREAS FOR FUTURE WORK

- 3-D stall inception
  - Models
  - Experiments
- Compressible, nonlinear modelling
  - Embedded volume dynamics must be explored
  - Coupling among modes
- Modelling with distortion
- Connecting compressor geometry to compressor slope
  - Prediction SOA is poor, especially near surge line
  - Must rigorously treat all loss, blockage, and deviation phenomena
- Active stability control
- Compressors with very high swirl (centrifugal machines)

Impact of Rotor-Stator Interaction on Turbomachinery Design:

Potential Areas of Future Research

Reza Abhari
Textron Lycoming
Stratford, CT

TEXTRON Lycoming

Outline

- Introduction
- Periodic unsteadiness and film cooling of turbine rotor (Heat Transfer)
- Rotor-stator interaction in a compressor stage (Performance)
  - Time accurate Navier-Stokes study by W.W. Copenhaver, S.L. Puterbauch and C. Hah
- Forced response and aero-damping (Aeromechanics)
- Conclusions

Periodic Unsteadiness Impacts Future Component Design

- **Turbine performance:**
  - Coolant injection losses
  - Secondary flow vortices interaction
  - Boundary layer transition (PT)
- **Turbine heat transfer:** (GP,LP)
  - Film cooling
  - Recovery temp. redistribution ("Phantom Cooling")
  - Heat transfer augmentation
- **Compressors performance:**
  - Mean flow redistribution (circumferentialy averaged)
  - Flow separation
  - Surge and stall prediction
- **Common to both turbines & compressors**
  - Unsteady aerodynamic forces
  - Aerodynamic damping
  - Noise

TEXTRON Lycoming

Turbomachinery Flow is Unsteady

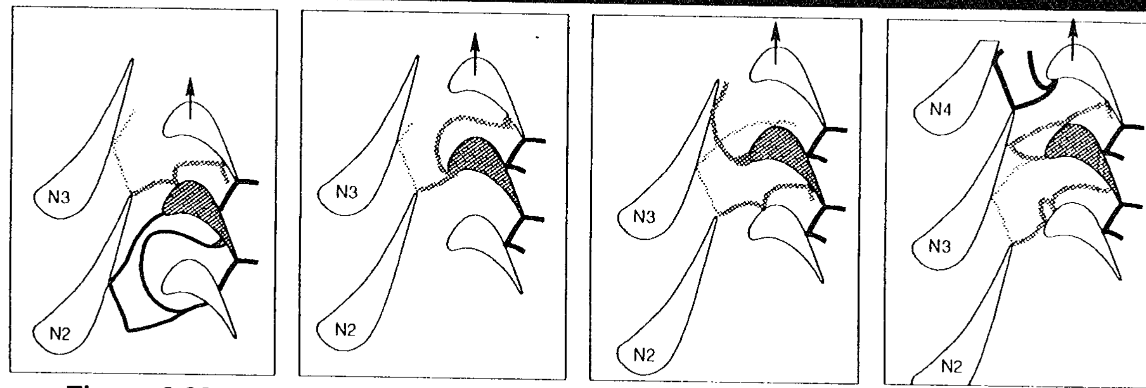
- A major cause of flow unsteadiness:
  - Relative motion of blade rows
- Present discussion:
  - Unsteady periodic flow
- Sources of periodic flow:
  - Potential flow field of adjacent rows
  - Upstream blade rows wakes
  - Upstream secondary flow vortices
  - Blade vibration
  - Other (vortex shedding, leakage flows, etc.)

"Highly" Unsteady Transonic Turbine Flow

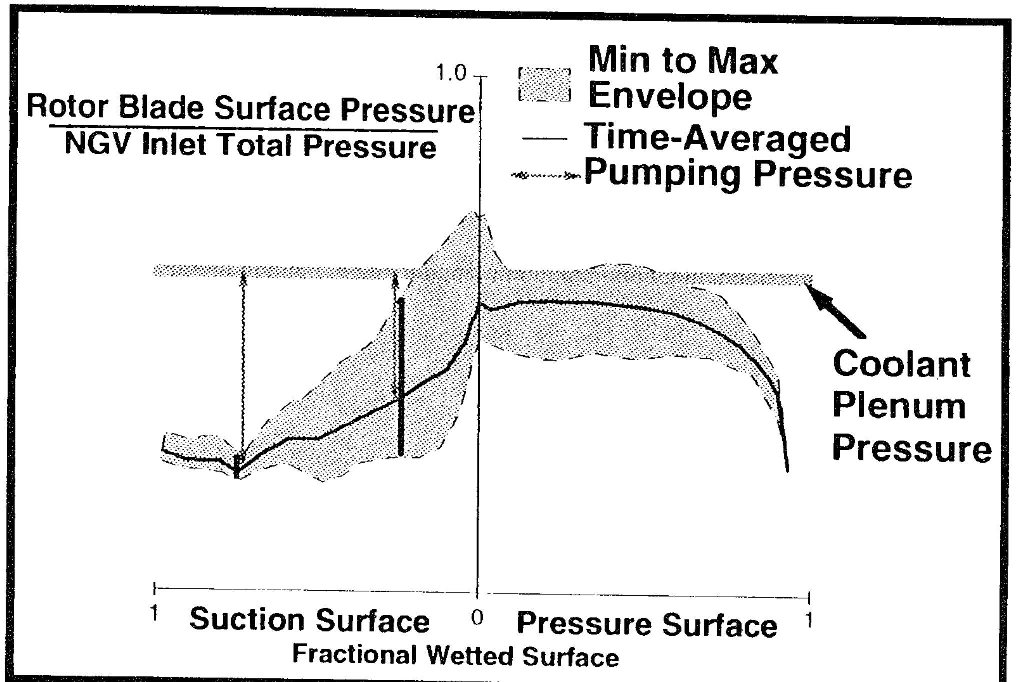
- Typical shock reflection in a Transonic Turbine

- Shocks could travel both upstream and downstream through multiple reflections

- When film cooled, periodic perturbations could be comparable in magnitude to (or much larger than) coolant pumping pressure



Time = 0.82 | Time = 1.11 | Time = 1.37 | Time = 1.6



TEXTRON Lycoming

Turbine Rotor- Stator Interaction and Heat Transfer

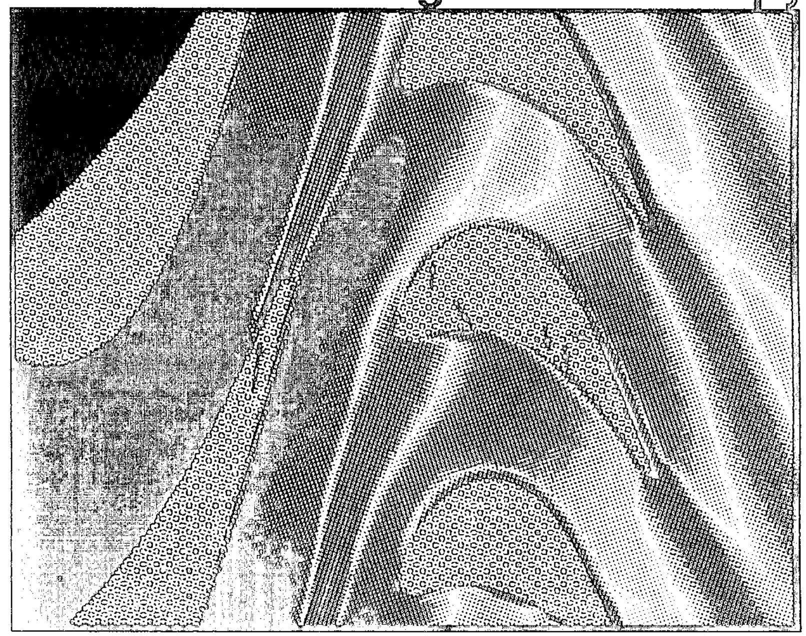
- Flow in a transonic gas producer (GP) turbine is very complex

- Turbine blade surface heat transfer is unsteady;
  Dunn, et.al. (1989), Guenette, et.al. (1989)

- Magnitude of unsteady heat flux is comparable to the mean level

- Contribution of periodic unsteadiness to time-average heat load not clear

Rotor Relative Stagnation Enthalpy



TEXTRON Lycoming

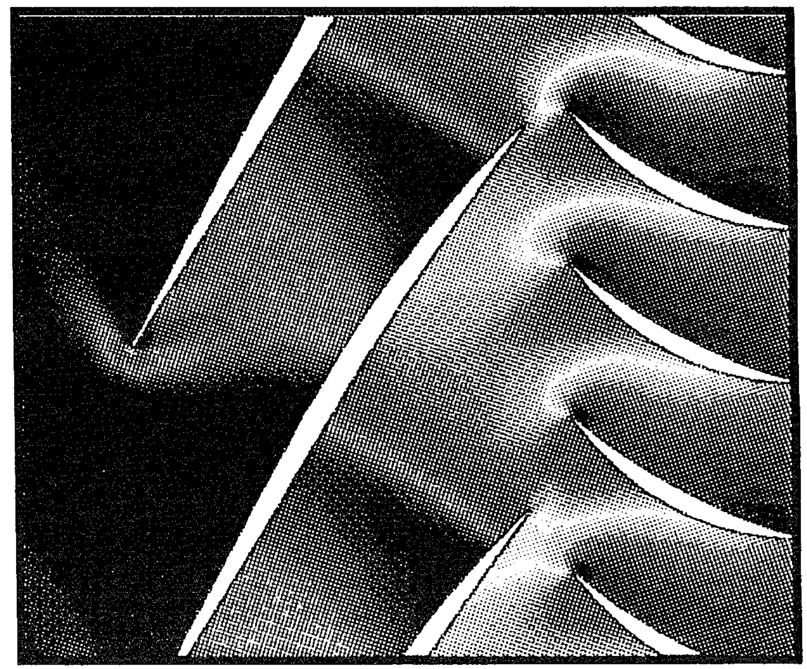
Rotor/Stator Interaction: Force Response

- Relative motion of blade rows results in unsteady aerodynamic force and moment on airfoils

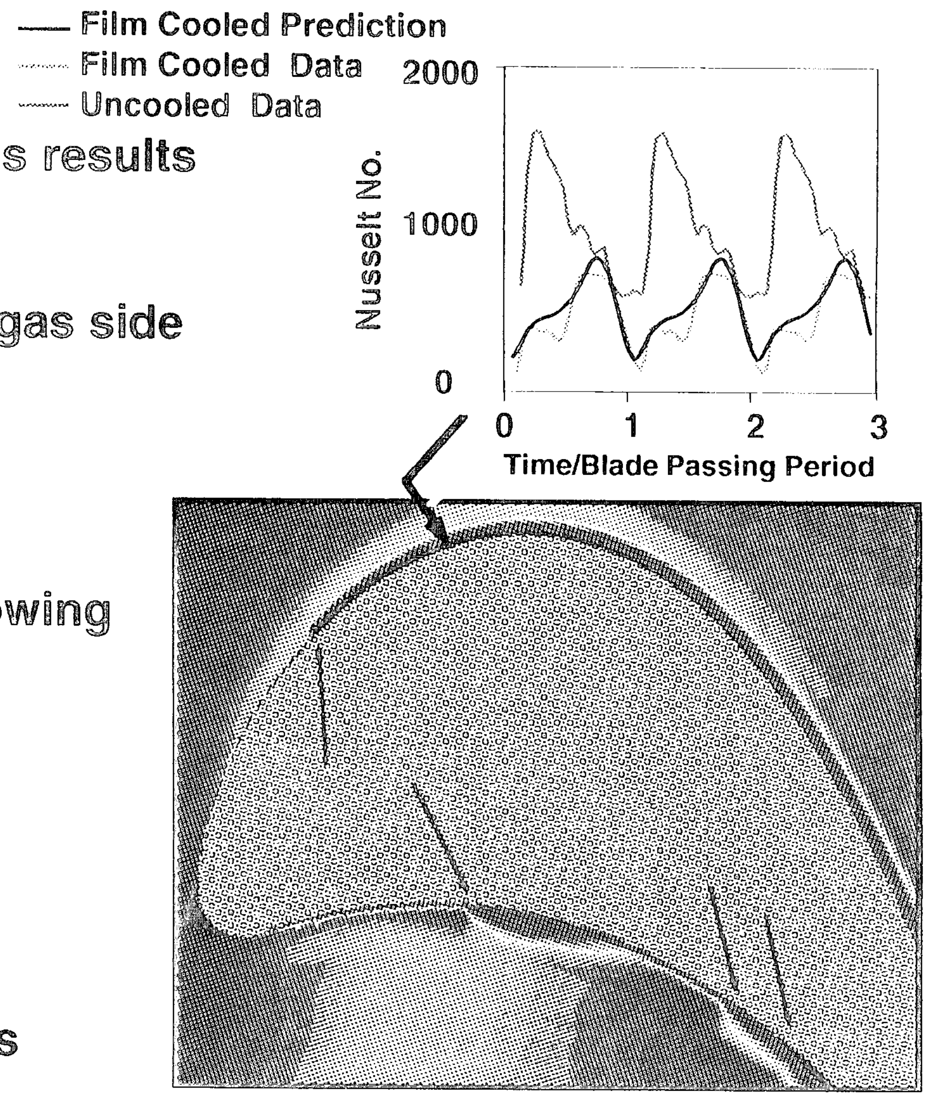
- Could result in blade failure at structural resonant frequencies

- Many computational approaches have been developed (primarily linearized models)

Pressure Contour



Flow Unsteadiness Impacts Film Cooling



- Large surface pressure fluctuations results in unsteady blowing
- Film Cooling becomes coupled to gas side periodic flow

- What is the impact of unsteady blowing on the mean surface heat flux?

- Further Work needed:
  - Detailed measurements
  - Development of design guidelines

TEXTRON Lycoming

Conclusions

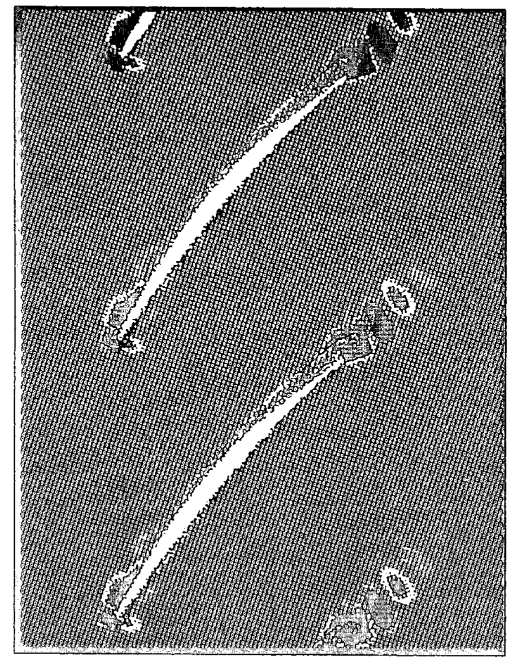
- Suggested areas of future research:
  - Periodic unsteadiness on film cooling of GP turbine blades
  - Rotor-stator interaction in compressor loss generation
  - Role of flow non-linearity in forced response prediction

- Some final thoughts:
  - Measurements and predictions are the initial steps in the understanding of unsteady flow.
  - Need to incorporate knowledge of rotor-stator interaction in our designs

Non-Linearity and Aerodynamic Damping

- Motion of blades at resonant frequencies provides aerodynamic damping
- For bladed disks (blisks), primary damping force opposing motion
- Use of linearized models is almost universal
- Modern airfoils:
  - Complex flow field
  - Low aspect ratio, "plate" like blades with complex vibratory motion
- It is not clear when linearized approach breaks down.

Unsteady Component of Vorticity



Non-Linear Viscous CFD
Solution With Blade Motion

DIRECT NUMERICAL SIMULATION OF TRANSITION AND TURBULENCE IN A SPATIALLY EVOLVING BOUNDARY LAYER

MAN MOHAN RAI
FLUID MECHANICS DIVISION
NASA LANGLEY RESEARCH CENTER

WINCAT, OCTOBER 4-6, 1993
PURDUE UNIVERSITY

APPROACH

- COMPRESSIBLE FLOW (SUBSONIC)
- NONCONSERVATIVE FORMULATION OF GOVERNING EQUATIONS
- HIGH-ORDER ACCURATE FINITE DIFFERENCES
- UPWIND-BIASING OF CONVECTIVE TERMS
- CENTRAL-DIFFERENCING OF VISCOUS TERMS
- ITERATIVE -IMPLICIT FRAMEWORK
- MULTIPLE ZONE DISCRETIZATION OF FLOWFIELD
- GENERATION OF NUMERICAL FREESTREAM TURBULENCE

BOUNDARY CONDITIONS

LOWER SURFACE : ADIABATIC WALL / NO-SLIP

UPPER SURFACE : SYMMETRY

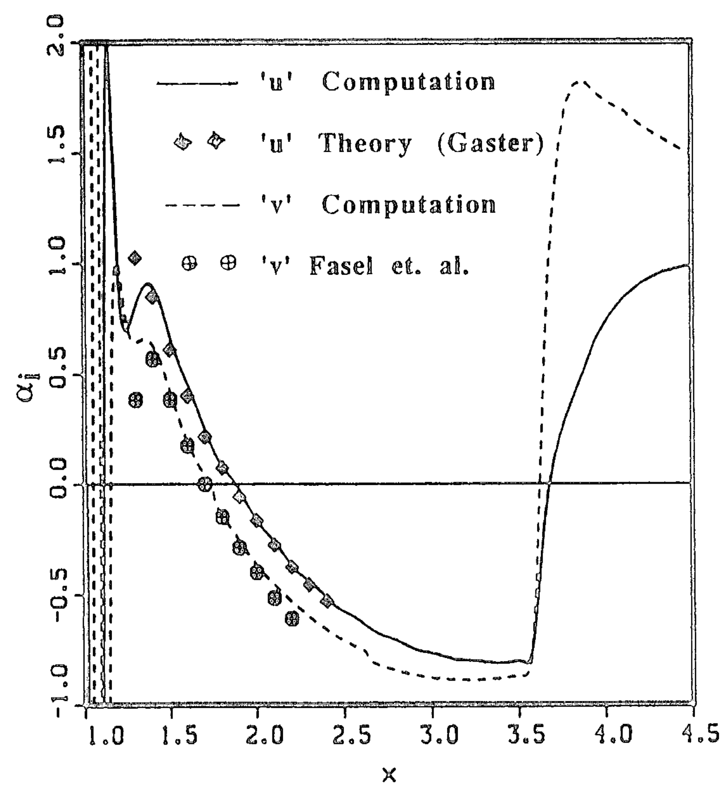
INLET BOUNDARY (ZONE 1) : VELOCITY PERTURBATIONS THROUGH RIEMANN INVARIANTS

EXIT BOUNDARY (ZONE 3) : PRESSURE REFLECTIVE CONDITION

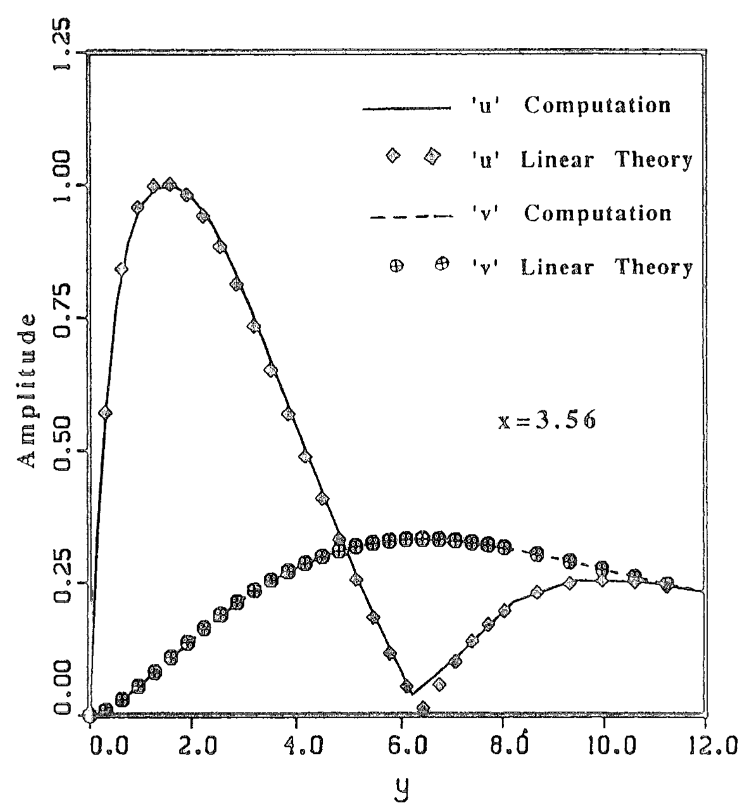
SPANWISE BOUNDARY SURFACES : PERIODICITY

EVOLUTION OF SMALL AMPLITUDE DISTURBANCES

GROWTH RATES



VELOCITY AMPLITUDES



COMPUTATIONAL PARAMETERS

LENGTH OF PLATE = 24.0 INCHES / 13.0 INCHES

WIDTH OF PLATE = 1.5708 INCHES

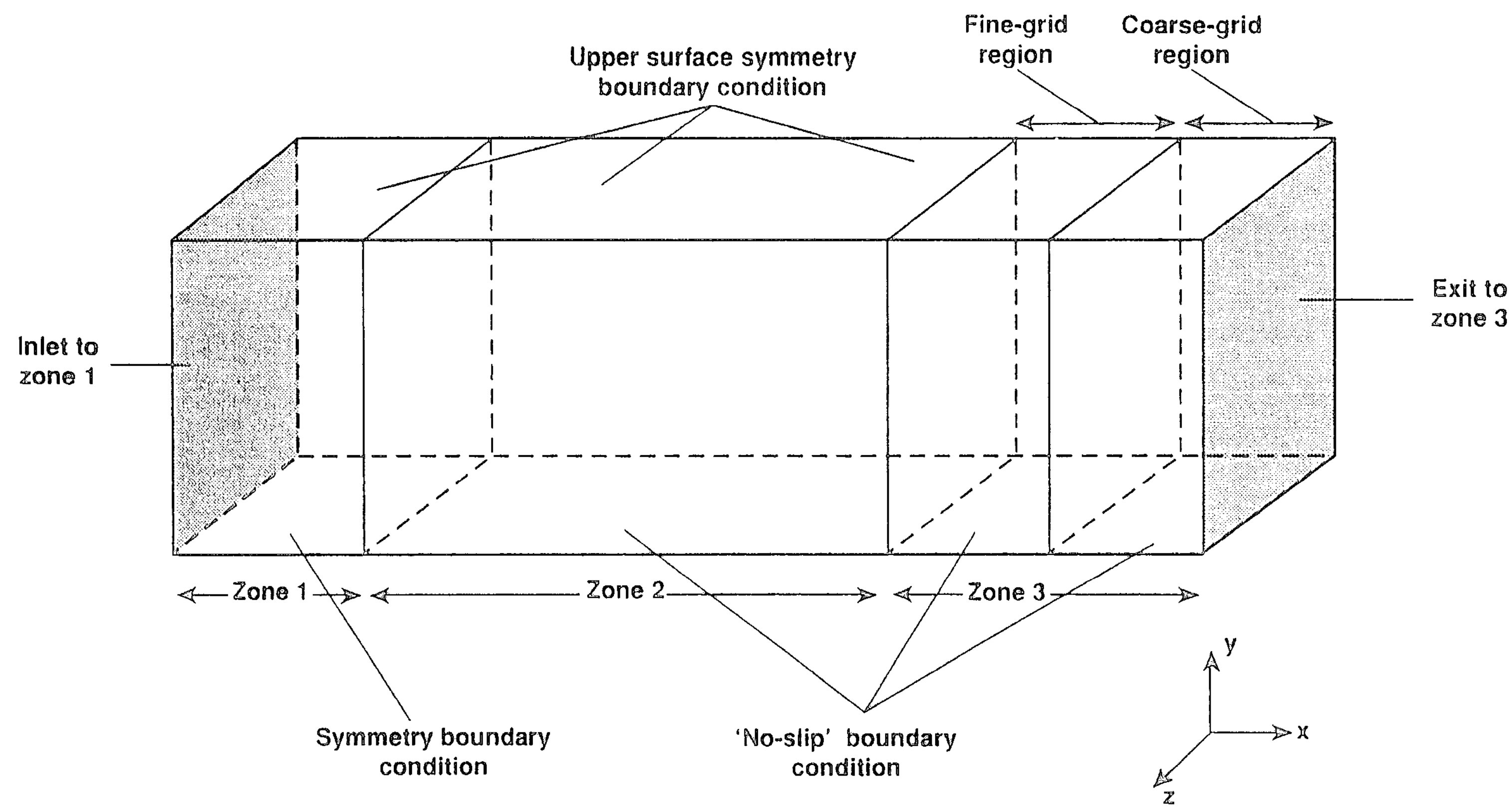
HEIGHT OF COMPUTATIONAL REGION = 3.0 INCHES

INLET MACH NUMBER = 0.1

INLET REYNOLDS NUMBER = 50000.0 / INCH

FREESTREAM TURBULENCE LEVEL = 2.7 % (NEARLY ISOTROPIC)

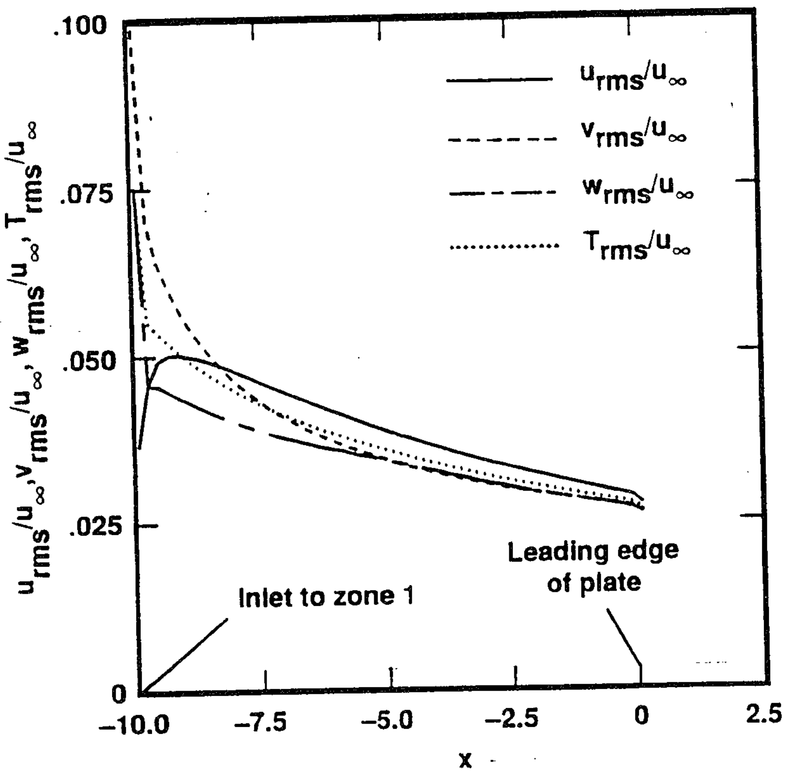
SCHEMATIC OF COMPUTATIONAL REGION (NOT TO SCALE)



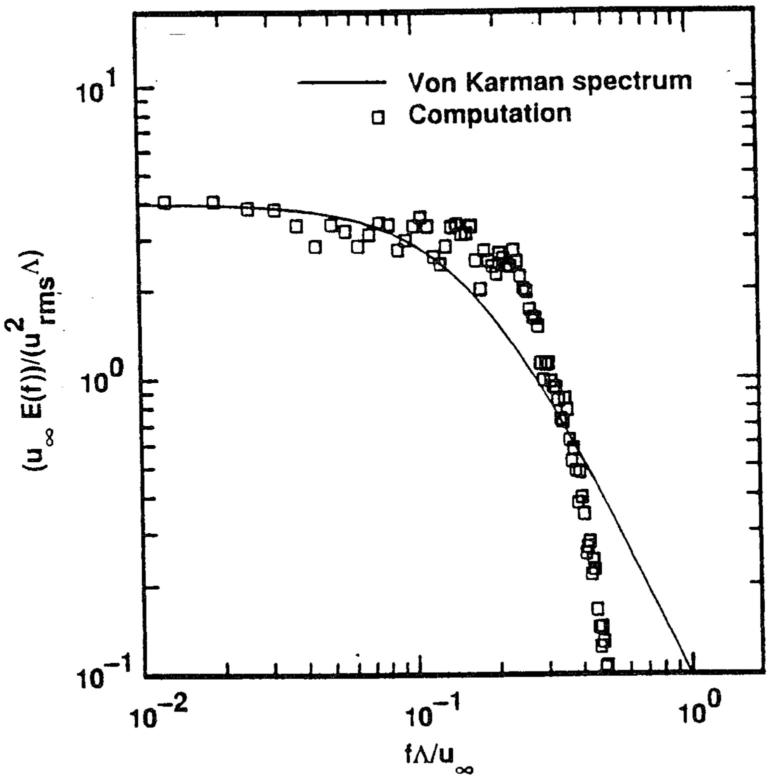
Rai-1a

CHARACTERIZATION OF FREESTREAM DISTURBANCES

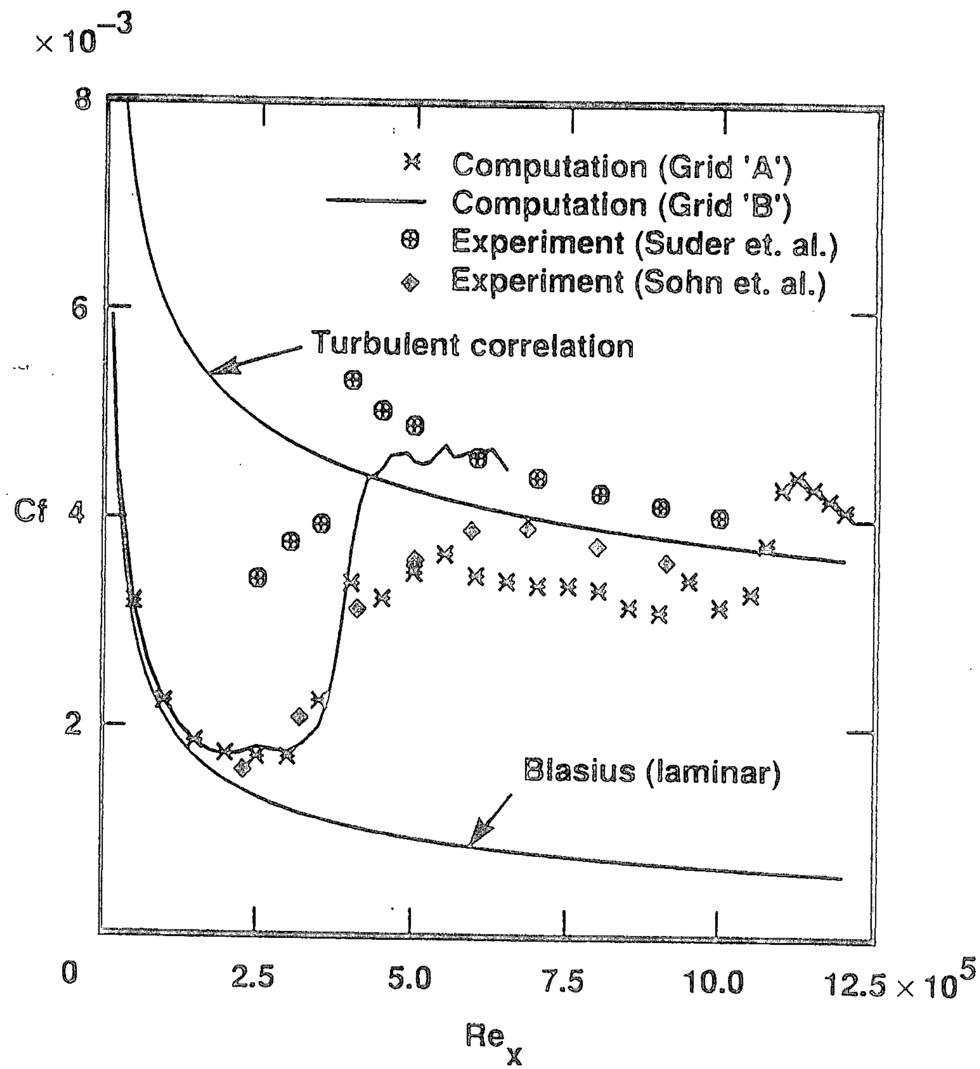
TURBULENCE INTENSITIES



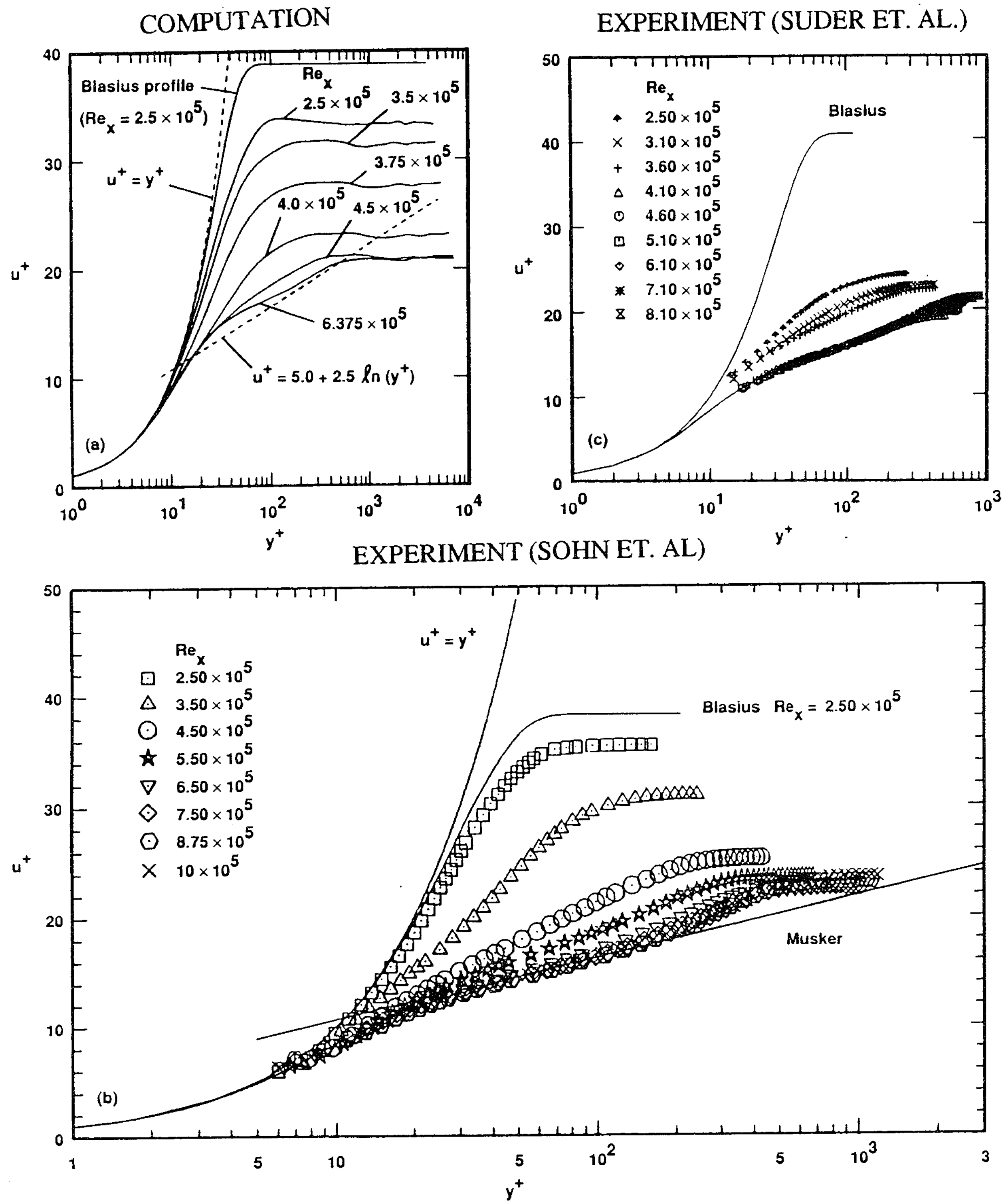
POWER SPECTRUM NEAR LEADING EDGE
(STREAMWISE VELOCITY COMPONENT)



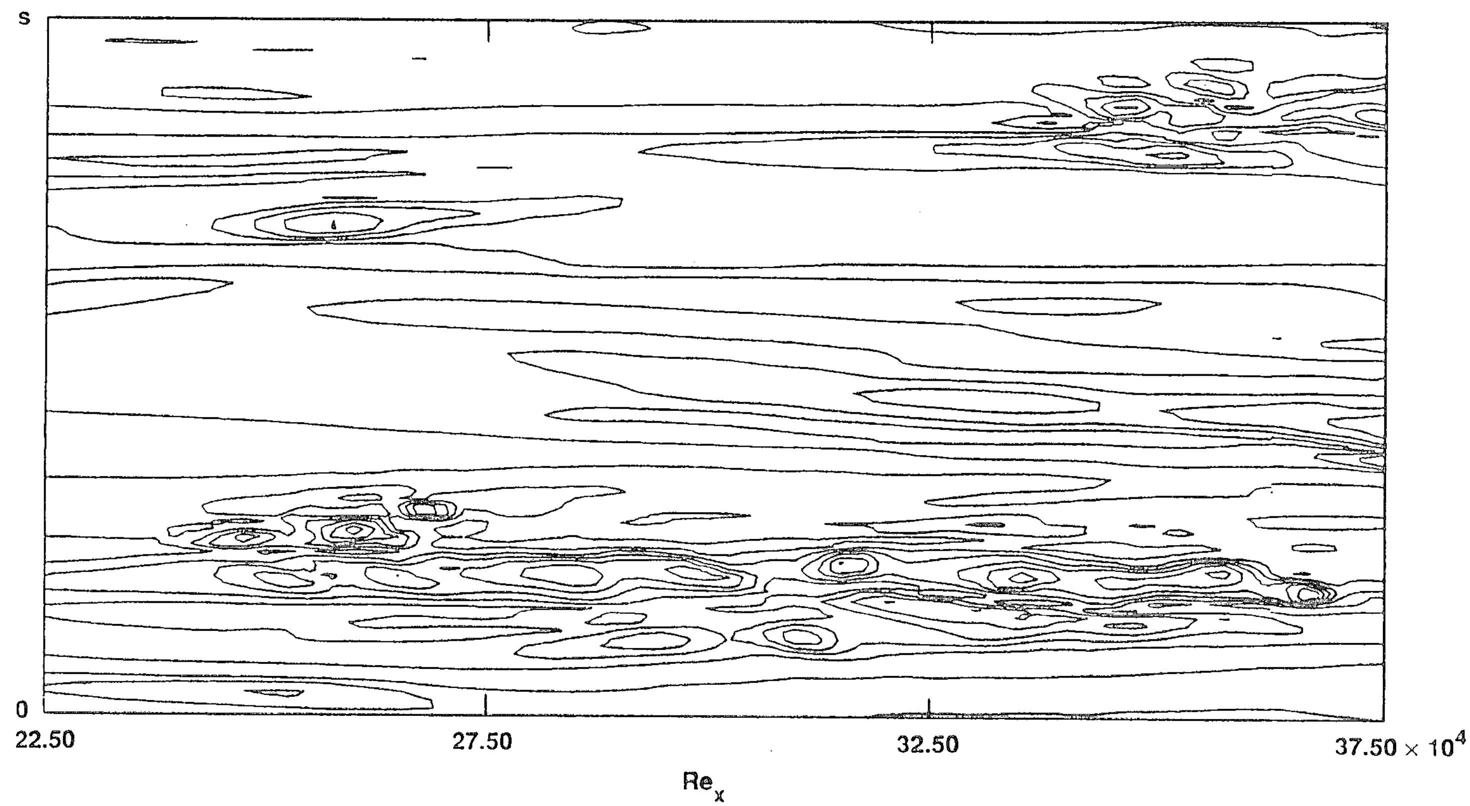
SKIN FRICTION ALONG FLAT PLATE



MEAN VELOCITY PROFILES

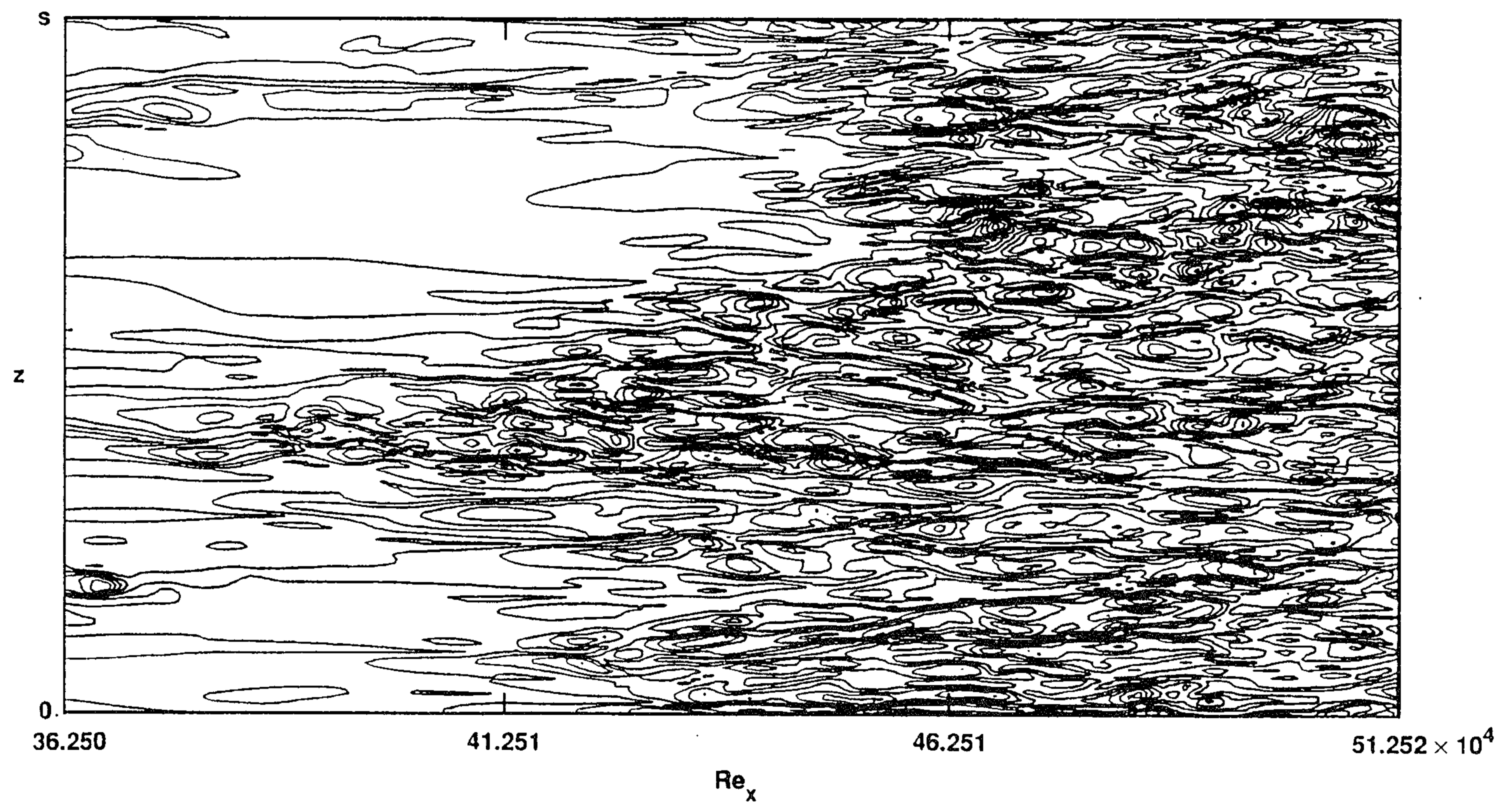


SPANWISE VORTICITY CONTOURS



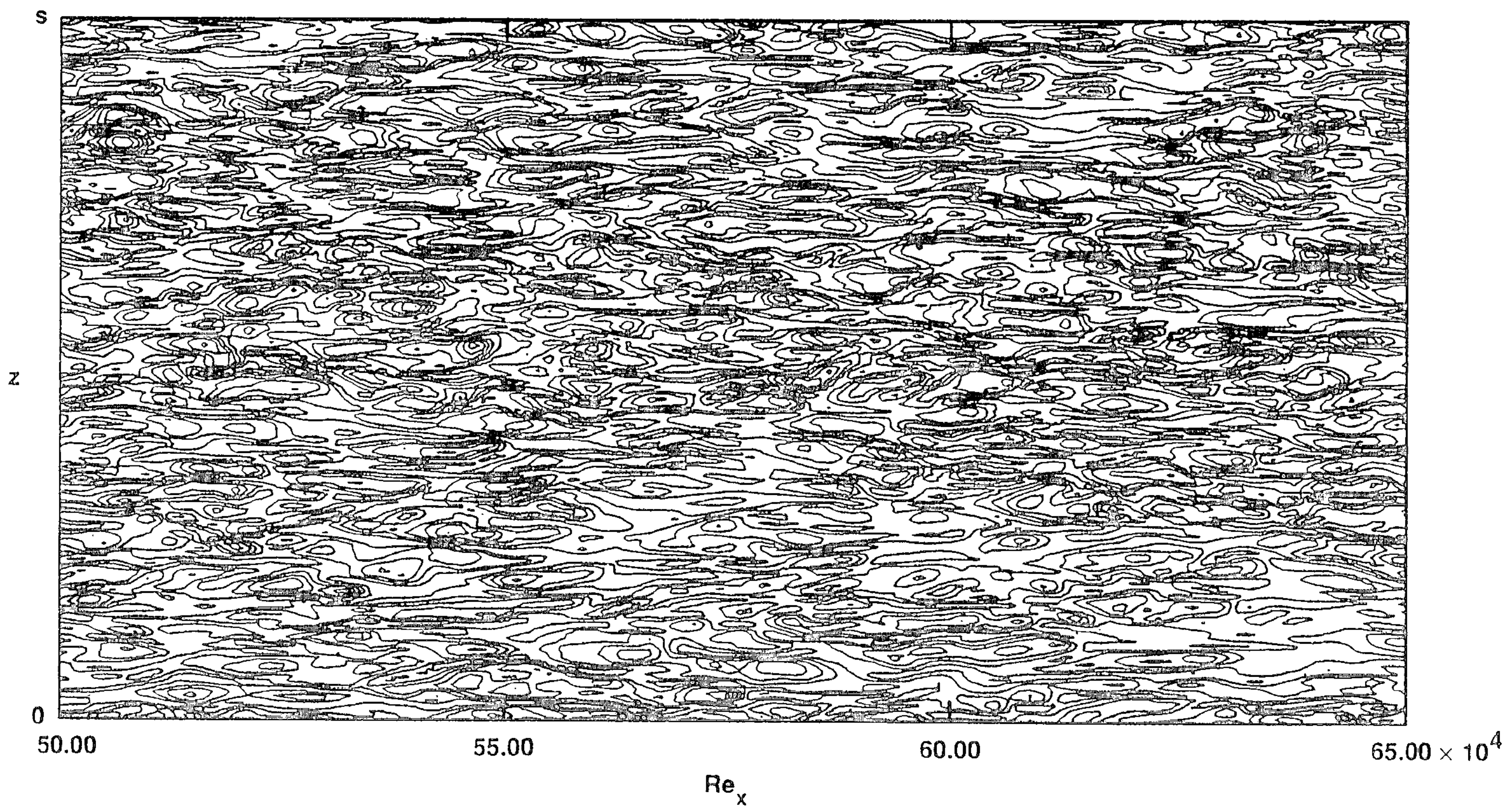
Rai-21

SPANWISE VORTICITY CONTOURS



Rai-22

SPANWISE VORTICITY CONTOURS



Rai-23

SUMMARY

- DEVELOPED A HIGH-ORDER-ACCURATE, UPWIND-BIASED, ITERATIVE-IMPLICIT, FINITE-DIFFERENCE APPROACH FOR DIRECT SIMULATIONS OF TRANSITION/TURBULENCE IN COMPRESSIBLE FLOW

- DEVELOPED AN ITERATIVE METHOD OF NUMERICALLY GENERATING FREESTREAM DISTURBANCES OF A PRESCRIBED NATURE

- DEVELOPED A CODE USING THE ABOVE TECHNIQUES FOR DIRECT SIMULATIONS OF FLAT-PLATE FLOW

- THE CODE EMPLOYS A ZONAL METHODOLOGY TO EFFICIENTLY USE THE TOTAL NUMBER OF GRID POINTS USED IN THE COMPUTATION

- COMPUTED ONE CASE OF HIGH-FREESTREAM-TURBULENCE TRANSITION ON TWO DIFFERENT GRIDS

- COMPUTED DATA AGREE QUALITATIVELY WITH EXPERIMENTAL DATA

- PRELIMINARY FLOW VISUALIZATION INDICATED THAT THE TRANSITION REGION WAS FOUND TO BE CHARACTERIZED BY DETACHED SHEAR LAYERS AND PAIRS OF COUNTERROTATING STREAMWISE VORTICES

SUMMARY.......CONTINUED

- RESULTS INDICATE THAT THE ESSENTIAL FEATURES OF THE TRANSITION PROCESS IN THIS PARTICULAR CASE HAVE BEEN CAPTURED

- A MORE REFINED GRID COMPUTATION WILL BE REQUIRED FOR DEMONSTRATING GRID INDEPENDENCE

- THE COMPUTING REQUIREMENTS FOR HIGHER MACH NUMBER COMPUTATIONS WILL BE SIGNIFICANTLY LESS THAN THAT REQUIRED FOR THE CURRENT COMPUTATION

- THE FINITE-DIFFERENCE METHOD USED IN THE PRESENT STUDY CAN IN A STRAIGHTFORWARD MANNER BE EXTENDED TO CURVILINEAR GRIDS

FUTURE DIRECTIONS

- HIGHER-ORDER ACCURATE ALGORITHMS FOR CURVILINEAR GRIDS
- ALGORITHMS SUITED FOR MASSIVELY PARALLEL COMPUTERS
- DIRECT AND LARGE EDDY SIMULATIONS OF AIRFOIL FLOW
- ROTOR-STATOR INTERACTION USING DS/LES TECHNIQUES

Three-Dimensional Flow Analysis inside Turbomachinery Stages with Steady and Unsteady Navier-Stokes Method

W. W. Copenhaver and S. L. Puterbauch
Aeropropulsion Laboratory
Wright Patterson AFB, Ohio 45433

C. Hah
NASA Lewis research center
Cleveland, Ohio 44135

APPROACH

- EXTEND A WIDELY TESTED STEADY CODE
- 2ND ORDER TIME ACCURACY
- 3RD & 2ND ORDER SPACE ACCURACY
- TWO-EQUATION TURBULENCE CLOSURE
- TRANSITION THROUGH LOW-REYNOLDS NUMBER (FREE STREAM TURBULENCE EFFECTS)

Rotor 4 Transonic Compressor Stage

Efficiency : 89.62 %

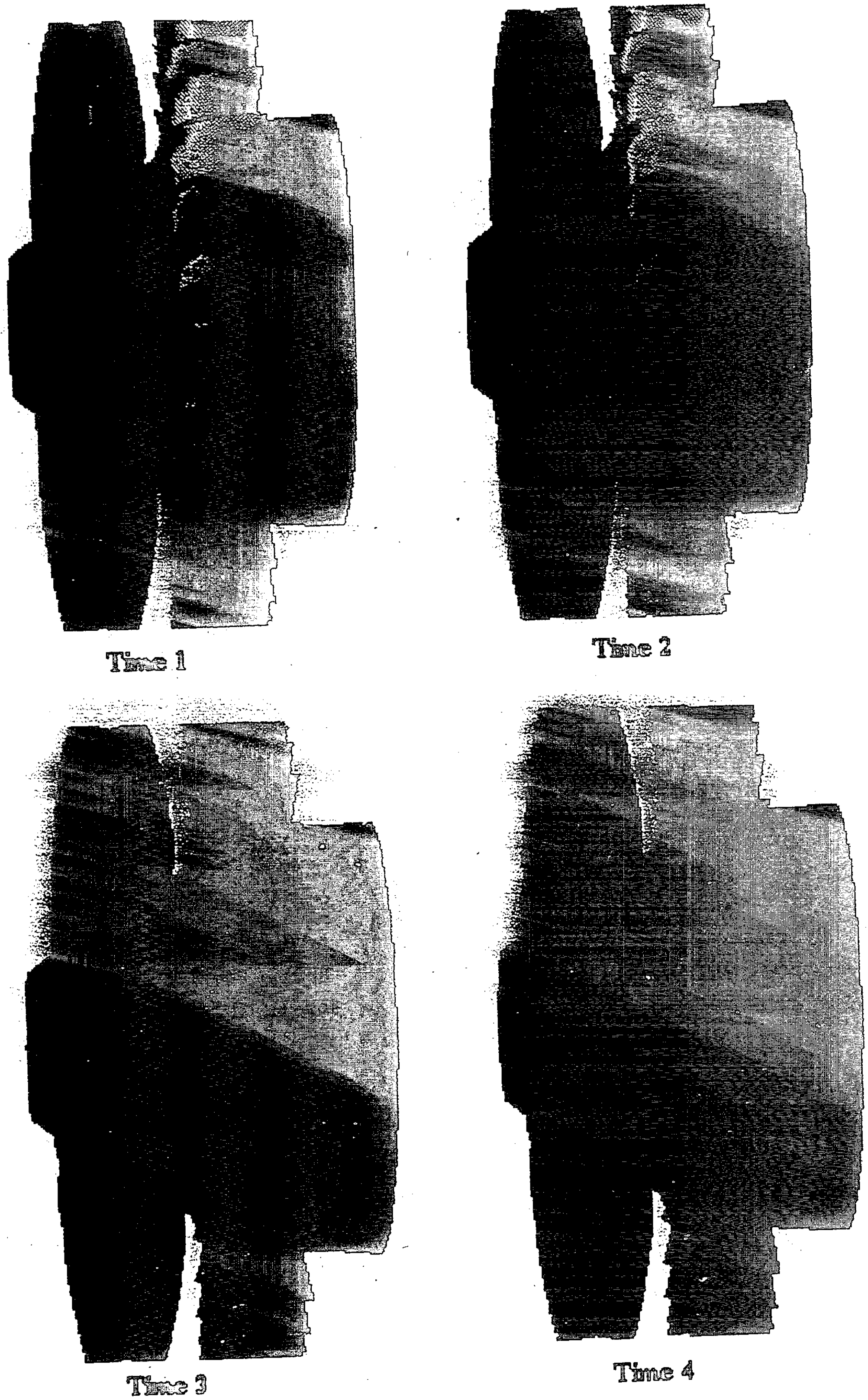
Pressure ratio : 1.988

Flow rate : 60.77 lb-m/sec.

Tip relative Mach number : 1.60

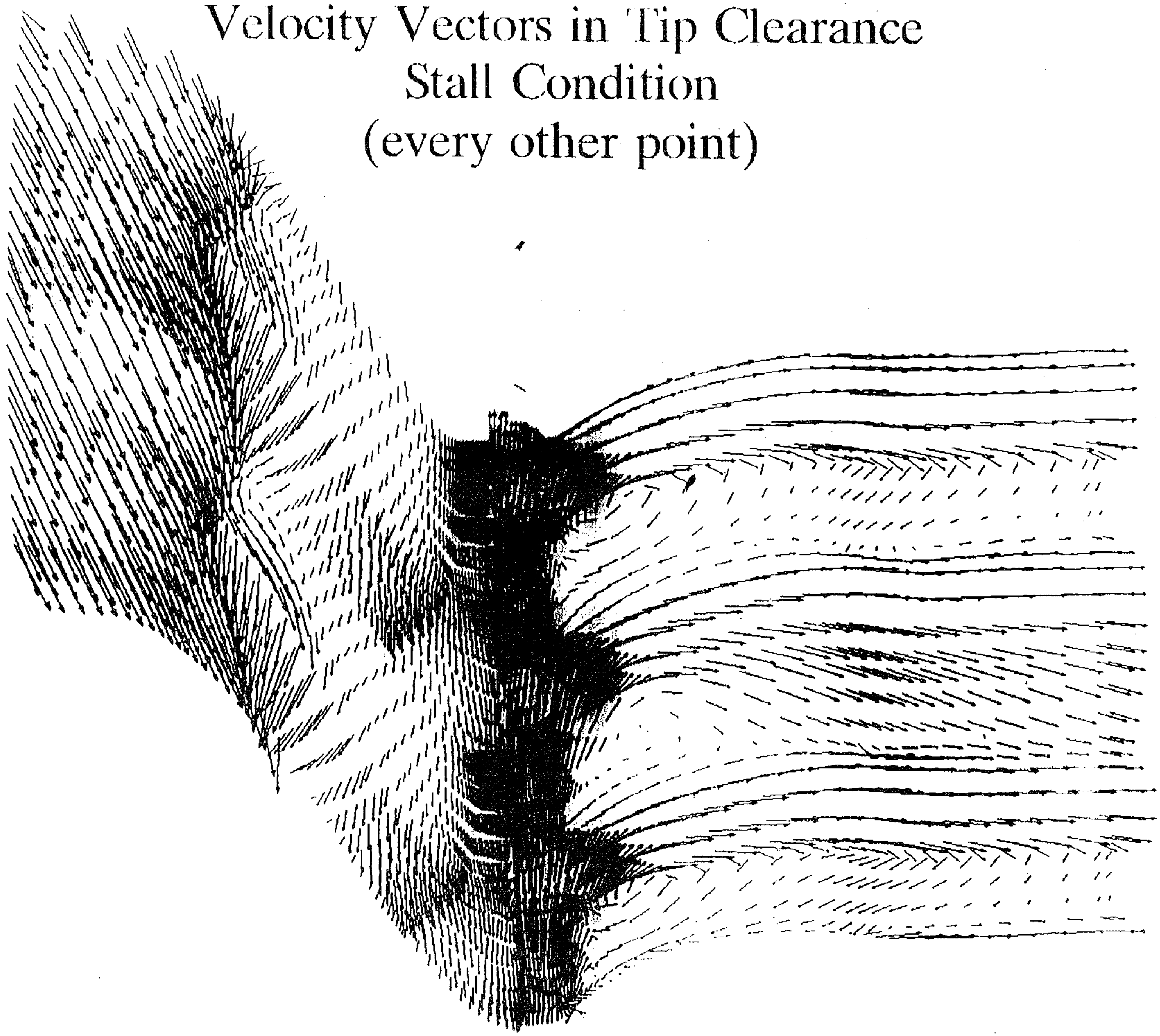
Tip speed : 1500 ft/sec.

Tip clearance : 0.5 % tip chord



Unsteady pressure distribution on compressor blades (stall condition).

Velocity Vectors in Tip Clearance
Stall Condition
(every other point)



SUMMARY OF THE BLUE MOUNTAIN WORKSHOP ON END-STAGE TRANSITION

Syracuse Univ.
Aug. 15-18, 1993

J. Lewalle for J.E. Lagraff
Dept. of Mechanical, Aerospace and Manufacturing Eng.
Syracuse University

JLAGRAFF@SUVM.SYR.Edu

Purpose of Workshop

Identify issues for future research

Topics

*Bursting

*Engineering Models

*Turbulent Spots and Breakdown

*3-D Numerics

*Working Groups as Needed

Conclusions

A. Experimental

*Transitional Flows are Common
*Need to Differentiate

TS-klebanoff "natural" transition
Bypass transition

*Key Issue: Receptivity

What acoustic/freestream features are dynamically relevant

*T-S sequence well understood, but how prevalent?

*Goal: Understand Freestream/Wall-Layer Interactions in Realistic Environments

Key Players: Blackweldes, Gantes, Kendall, Morkovin, Noaenchuck, Simon, Gostelow, Jones ....

B. Computational

*Complexity can now be captured

*Generation of Databases

*Need to coordinate with practitioners so the right data are extracted

Key Players: Rai, Sandham, Singes

C. Analytical

*Understanding for modeling

Key Players: Smith, Herbst

D. Modeling

*Model the <u>physics</u>, not the numbers

*Onset is critical for modeling

*Intermittency modeling insensitive to physics

*Poor understanding of spot/flow interactions

*Poor understanding of receptivity/spot relation

Key Players: Reshotko, Nasasimho, Crawford, Ashworth, Hedson

MINNOWBROOOK CONFERENCE
End-Stage Transition W shop
15-18 August

Sunday - 15 August 1993

2:30 pm	Minnowbrook Center Open to Participants
3 - 5:30 pm	Visit to Adirondack Museum (optional)
6:00 pm	Dinner
7:30 pm	Organization Comments - **John E. LaGraff** - Syracuse University Introduction to Goals and Focus of Workshop - **J.P. Gostelow**
8:00 pm	**R. Narasimha** (30 minutes) - Indian Institute of Science The Many Worlds of Transition Research
9:00 pm	Social

Monday - 16 August 1993
8:00 am Session 1 - Approach to Bursting

moderator:	**Jacques. Lewalle** -Syracuse University
8:00 am	**M.V. Morkovin** - Keynote - (30 min) - Illinois Institute of Technology From Disturbances to Instabilities to Breakdown to Turbulence: The Physics of Transition in Boundary Layers
8:30 am	**R.E. Blackwelder** - Univ. of So. California Initiation of Turbulent Spots in a Laminar Boundary Layer by Rigid Particulates (with F.K. Brownand, C. Fisher, and P. Tanaguichi)
8:45 am	**J.M. Kendall** - California Inst. of Technology Experiments on Wave Packets Induced Ahead of Transition by Freestream Turbulence
9:00 am	**M. Gaster** - Cambridge University The Evolution of Modulated Wavetrains into Turbulent Spots
9:15 am	**D. Nosenchuck** - Princeton University Active Control of Transition Using Lorentz Force (with Dr. G. Brown)
9:30 am	Discussion

BREAK

10:30 am Session 1a

moderator: Edward A. Bogucz - Syracuse University

10:30 am T.C. Corke - Illinois Institute of Technology
Role of Detuning in the Final Stage of Subharmonic Mode Transition in Boundary Layers

10:45 am F. Smith - University College - London
Nonlinear Theory and Breakdown (with Dr. R. Brown)

11:00 am C. Smith - Lehigh University
Development of Hairpin Vortices in Turbulent Spots and End-Wall Transition

11:15 am B. Singer - NASA Langley Research Center
Hairpin Vortices and the Final Stages of Transition

11:30 am Discussion

12:15 LUNCH

2:00 pm Session 2 - Engineering Models and Turbomachinery Applications

moderator: T. Okiishi - Iowa State University

2:00 pm H. Hodson - Keynote (30 min)
Transition in Turbomachines

2:30 pm C. Fraser - Dundee Institute of Technology
Transition Models for Engineering Calculations

2:45 pm D.A. Ashworth - Rolls Royce Plc.
Intermittency Models and Spot Measurements

3:00 pm G.J. Walker - University of Tasmania
Boundary Layer Transition on an Axial Compressor Stator Blade

3:15 pm Discussion

BREAK

4:15 pm Session 2a

moderator: M. Crawford - University of Texas

4:15 pm T. Wang- Clemson University
Heat Transfer in Boundary Layer Transition

4:30 pm	**T. Okiishi** - Iowa State University Boundary Layer Transition and Separation in a Turbine Cascade
4:45 pm	**D.Wisler** - General Electric Company Characteristics of Boundary Layer Transition in a Multi-Stage Low-Pressure Turbine
5:00 pm	**F. Simon** - NASA Lewis Research Center A Research Program for Improving Heat Transfer Prediction Capability for the Laminar to Turbulent Transition Region of Turbine Vanes/Blades
5:15 pm	**M. Platzer** - Naval Post Grad. School Leading Edge Separation Bubbles
5:30 pm	Discussion
7:00 pm	Dinner

Tuesday - 17 August 1993
8:00 am Session 3 - Turbulent Spots & Breakdown

moderator:	**E.F. Spina** - Syracuse University
8:00 am	**I. Wygnanski** - Keynote (30 min) - University of Arizona University of Arizona
8:30 am	**J.P. Gostelow** - University of Technology Some Scenarios for Transition on Turbomachinery Blading
8:45 am	**T.V. Jones** - University of Oxford Turbulent-Spot Growth Characteristics: Wind-Tunnel and Flight Measurements of Natural Transition at High Reynolds and Mach Numbers
9:00 am	**I. Poll** - University of Manchester Intermittent Turbulence in the Attachment Flow Formed On an Infinite Swept Wing
9:15 am	**T. Cebeci** - California State University The Role of Separation Bubbles on the Aerodynamic Characteristics of Airfoils, Including Stall and Post-Stall
9:30 am	Discussion

BREAK

10:30 am Session 3a

moderator:	**T.V. Jones** - Oxford University
10:30 am	**R. Kimmel** - Wright Patterson Air Force Base Late Stage Hypersonic B.L. Transition

10:45 am T. Simon - University of Minnesota
Experiments in Transtional Boundary Layer with Emphasis Free Stream Disturbances Level, Surface Curvature and Streamwise Pressure Gradient Effects (with Ralph Volino)

11:00 am A. Seifert - Tel-Aviv University
On the Evolution of Localized Disturbances and Their Spanwise Interactions Leading to Breakdown

11:15 am E. Malkiel - Rensselear Polytechnic University
Transition in Separating-Reattaching Boundary Layer Flows (with Prof. R.E. Mayle)

11:30 am - Discussion

12:15 LUNCH

2:00 pm Session 4 - Numerical & 3-D Effects

moderator: S. Robinson - NASA LARC

2:00 pm E. Reshotko - Keynote (30 min)- Case Western Reserve
Transition Zone Modeling

2:30 pm T. Herbert- Ohio State University
Simulations of Boundary Layer Transition

2:45 pm M.M. Rai - NASA Langley Research Center
DNS of Transition & Turbulence in a Spatially Evolving Boundary Layer

3:00 pm N.D. Sandham - Queen Mary and Westfield College of Trans.
Numerical Simulation of the Last Stages of Transition

3:15 pm M. Crawford - University of Texas
Performance of k-ε Turbulence Models in the Simulation of Bypass-Level Transition

3:30 pm Discussion

BREAK

4:30 pm Session 4a
working group meeting

6:30 pm Dinner

Wednesday - 15 August 1993

8:00 am Report of Session Chairs/moderators
Report of ad-hoc working groups?
Wrap-up discussion

10:00 am Conclusion of workshop

10:30 am	Vans leave for Syracuse airport
12 noon	Lunch for remaining participants
1:00 pm	Vacate center

8/12/93

Klod Kokini

School of Mechanical Engineering
Purdue University

HIGH TEMPERATURE CERAMIC COATINGS IN TURBOMACHINERY

HIGH TEMPERATURE CERAMIC COATINGS IN TURBOMACHINERY

Klod Kokini

School of Mechanical Engineering
Purdue University
West Lafayette, IN 47907
(317) 494-5727

BACKGROUND

* The next generation of turbomachinery requires the use of high temperature coatings in order to survive the application of increasingly large thermal loads.

* The criteria necessary to design these coatings are currently not known and need to be determined.

OBJECTIVES

1. To develop a fundamental understanding of failure and fracture mechanisms and develop life models of high temperature ceramic coatings.

2. To study the coupling between the unsteady fluid mechanics, the heat transfer and the thermomechanical behavior of the coated structure.

3. To translate this information into guidelines which can be used to design high temperature coatings for advanced turbomachinery.

BROAD RESEARCH ISSUES

1. Effects of the dynamic, high temperature environment existing in turbomachinery on crack initiation and crack propagation processes in the coating and at the interfaces.

2. Effects of the coating and its surface on the unsteady fluid mechanics problem, in particular, the separation and transition of the flow.

3. Effects of the coating on the unsteady heat transfer problem.

4. Solution of the coupled, unsteady fluid mechanics, heat transfer, thermomechanics and materials problem.

5. Measurements at high temperatures.

INTERDISCIPLINARY RESEARCH

* Fluid Mechanics
* Heat Transfer
* Thermomechanics
* Materials

CAPABILITIES

- Experimental

  * High intensity focused infra-red lamps.
  * High power (1.5kW) laser.
  * High temperature (1700 C) furnace.
  * 22 kip MTS Universal Testing Machine.

-Analytical

  * Thermomechanics.
  * Thermal fracture and fatigue.
  * Interface fracture mechanics.
  * Interface edge stresses.

High Frequency Engine Control

H. Austin Spang, III

GE Research and Development Center

Schenectady, NY 12301

(518) 387-6490

October 5 1993

CRD CSL

Long Range Vision

"Smart" High Frequency Engine Control

- Compressor stabilization
- Combustor stabilization
- Active noise control
- Active rotor dynamic control
- Active control of aeroelastic instability

Limited dynamic models means simulation provides at best limited verification.

Experimental development required

Active Control of Stall

- <u>Current assessment:</u>

  Active control of surge needs on-engine experimentation & trail.

  Active control of rotating stall needs further fundamental work - theory, actuators, sensors.

- <u>To close the gap between researchers and engine manufactures:</u>

  Experiments and proof of concept must shown experimentally

  Most credible using a full engine.

    Surge control must be on a full engine.

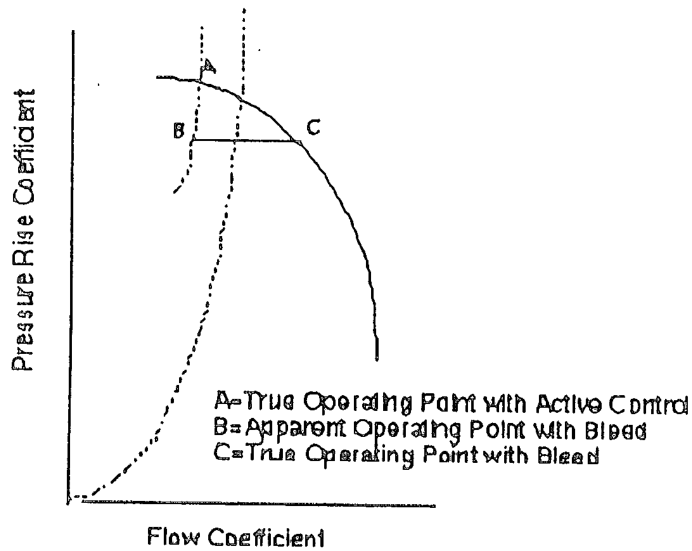
  Many practical problems need to be sorted out

    Sensors, actuators, and control bandwidth.

  Size of engine not as important as type and design of compressor.

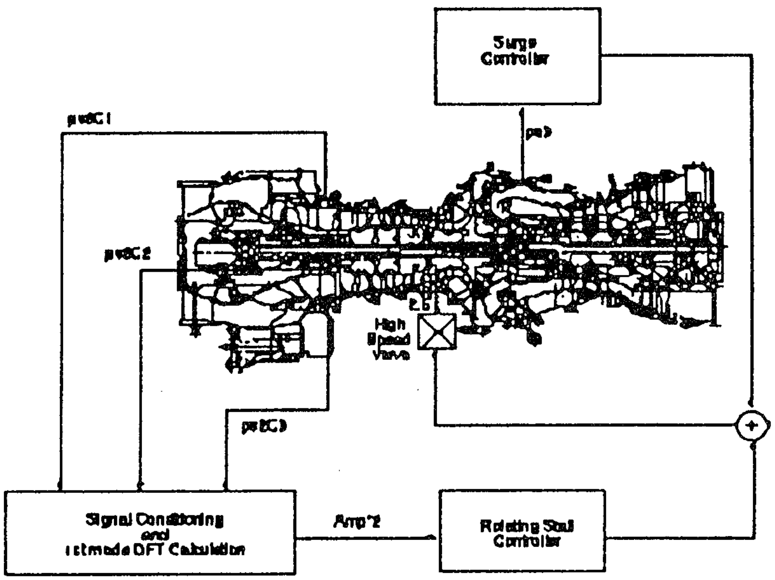
CRD CSL

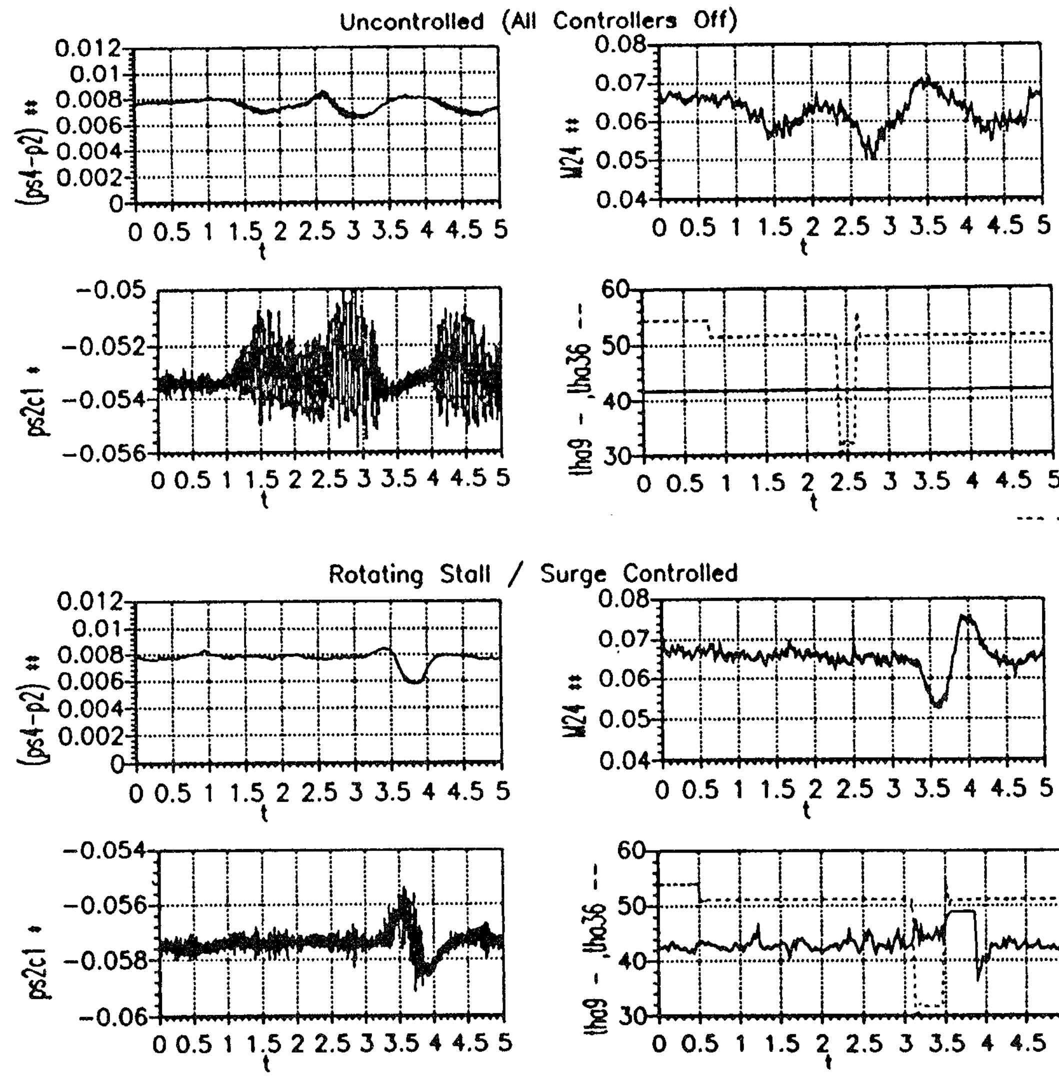
Difference Between Active Control of Surge Stall and Stall Avoidance



- Stall avoidance (Bleed)
  - Allow low net flow by bleeding exess air from compressor.
  - True operating point is C.
- Active Control
  - Stabilizes compressor with low flow.
  - True operating point is A.

Control strategy for surge and minimizing stall





Control of surge and rotating stall

Iver Day - Whittle Laboratory

4 stage Compressor

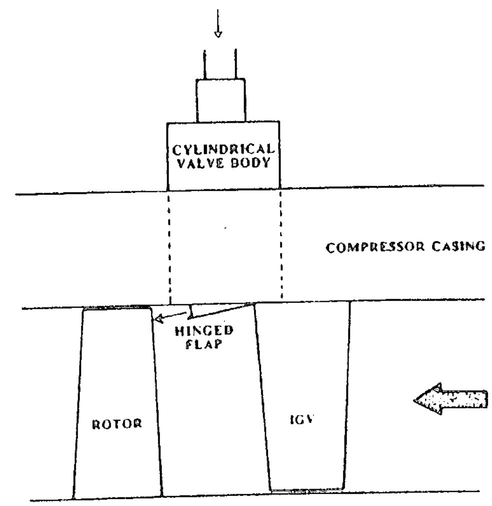
  3000 rpm, low pressure ratio

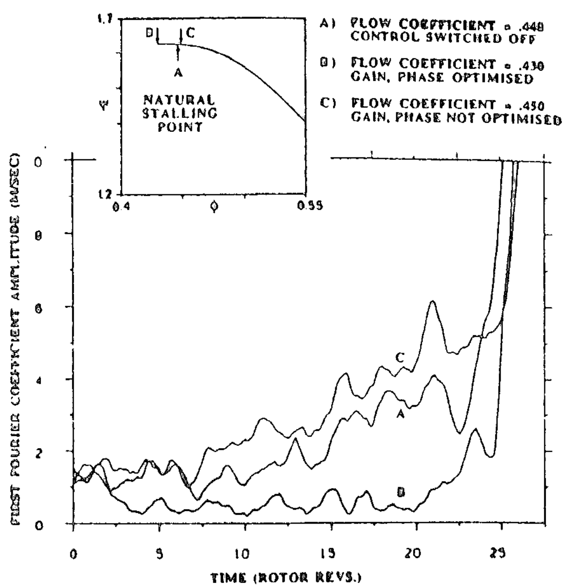
Hot-wire anemometers

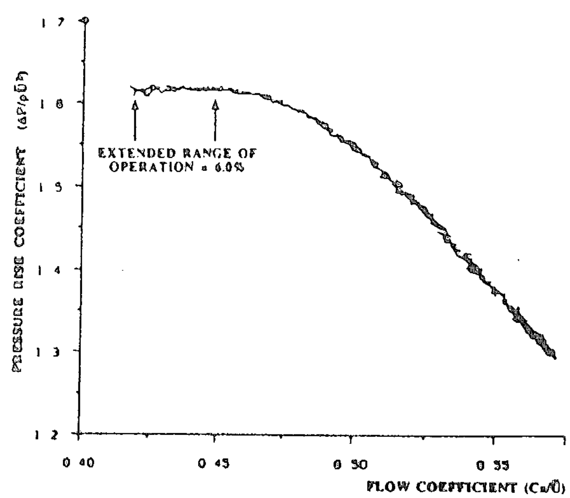
12 "puffer" valves between IGV and 1st rotor

Stabilizes by blowing short 3ms puffs at the boundary of compressor flow.

Approximately 1% of main flow, allows compressor flows 5-7% lower than usual.







CRD CSL

Research and Development Needs

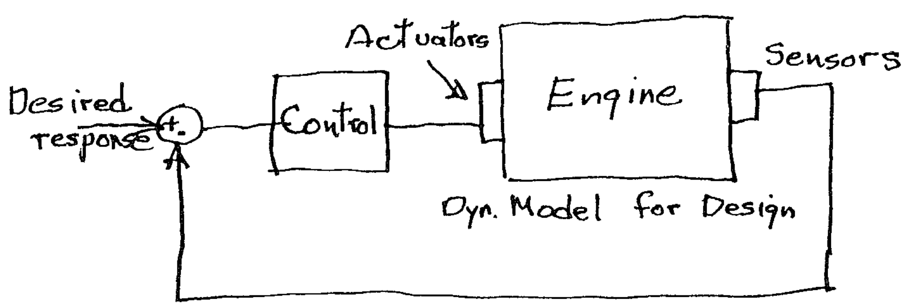
- Develop technology to allow engine designers to apply active stabilization:

  High frequency (20-500hz) dynamic modeling

  Development of actuators and sensors

  Development of robust control strategies

- Need to have on going engine experiments/tests during development
- Periodic engine demonstrations to focuses technology development



CRD CSL

Dynamic Modeling

Objective:

Develop models which allow off-line control design and capture effects of :

- High frequency dynamics
- Engine structure and components
- Engine tolerances and uncertainty
- Sensors and actuators on controllability and uncertainty

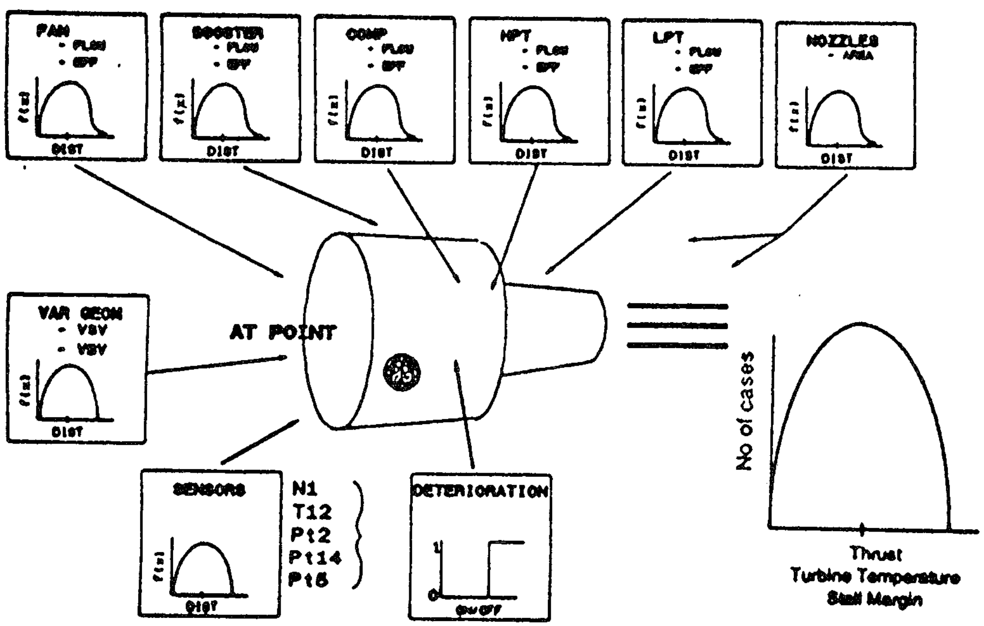
State-of-the-art:

- Qualitative behavior model (MIT)
- Detail component level model (GA Tech)

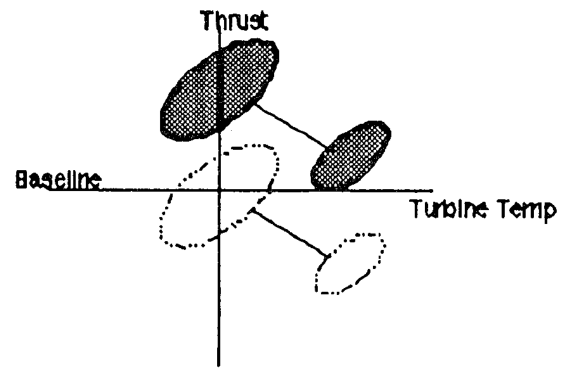
What level of detail is needed?

How much uncertainty can be tolerated?

Engine Variation



Thrust versus Turbine Temperature



Active Control of Surge /Stall must stabilize over this variation.

No on-line tuning

CRD CSL

Sensors and Actuator Development

Objective:

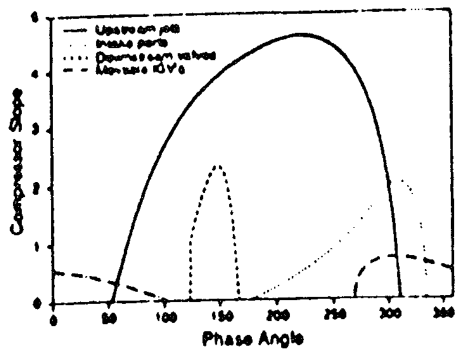
Develop actuators and sensors with required bandwidth

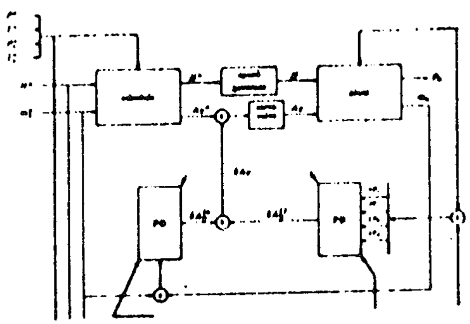
Development needs:

- Analysis and experiments into most effective approach with respect to controllability and uncertainty
- High bandwidth sensors suitable for flight operation
- High bandwidth actuators

Need experimental prototype development.

Actuators and Sensors for Active Control of Surge/Stall



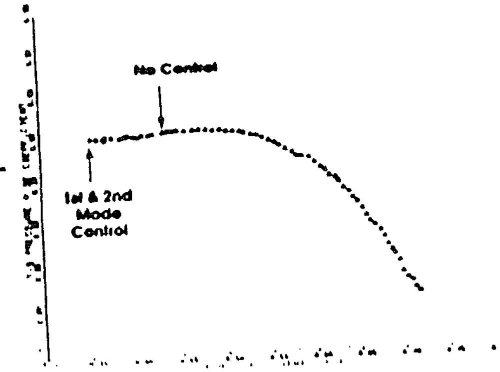


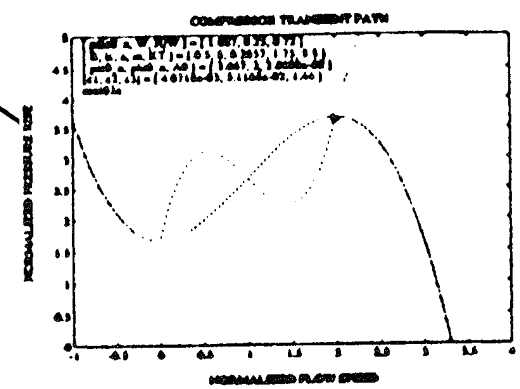
Actuators:

- Inlet Guide Vanes
- Inlet jets
- Dynamic bleed

Sensors:

- Pressures
- Temperatures
- Model based estimation of axial velocity





Need to develop practical high speed (200-400hz) actuation.

Experimental verification essential.

CRD CSL

Control Strategy Development

Objective:

- Develop a methodology to allow active surge/stall control to be designed off-line and shown to work without on-line tuning.
- Handle uncertainty from unmodeled dynamics and design tolerances.
- Non-linear control approaches to achieve full range operation.
- Handle interactions between active control and conventional engine control.

Off-line control strategies which do not require on-line tuning.

Research and Development Needs

- High frequency (20-500hz) engine system/compressor modeling.
  - Models relating known physical characteristics to dynamic response.
- Compressor characterization in the in-stall region.
  - Experimental verification.
  - Need to develop forced response techniques for incremental stabilization and identification.
- Analytical and experimental study of possible actuators and sensors which are usable on an engine - high frequency (20-400hz) rrequired.
- Development of robust control strategies to handle:
  - Uncertainty from unmodeled dynamics and design tolerances
  - Off-line design without on-line tuning
- Periodic engine demonstrations to focuses technology development

CRD CSL

Cooperative Research Proposal for Active Stall Control in Large Engines

Goal
Challenge
Approach
Obstacles
Research Plan

G. W. Gallops
Pratt & Whitney GESP
January 27, 1992

ASC Goal

Reduce compression system stall pressure ratio requirements by five to ten percent.

Subsonic A/C

5 - 10% SPR = 2 - 5% TOGW = 2 - 5% Range

Supersonic A/C

5 - 10% SPR = 2 - 5% T/W = 2 - 5% TOGW

Other Benefits

High frequency disturbance rejection:
inlet, combustion, water & exhaust ingestion.

Improved stall avoidance & recovery.

Improved combustion stability.

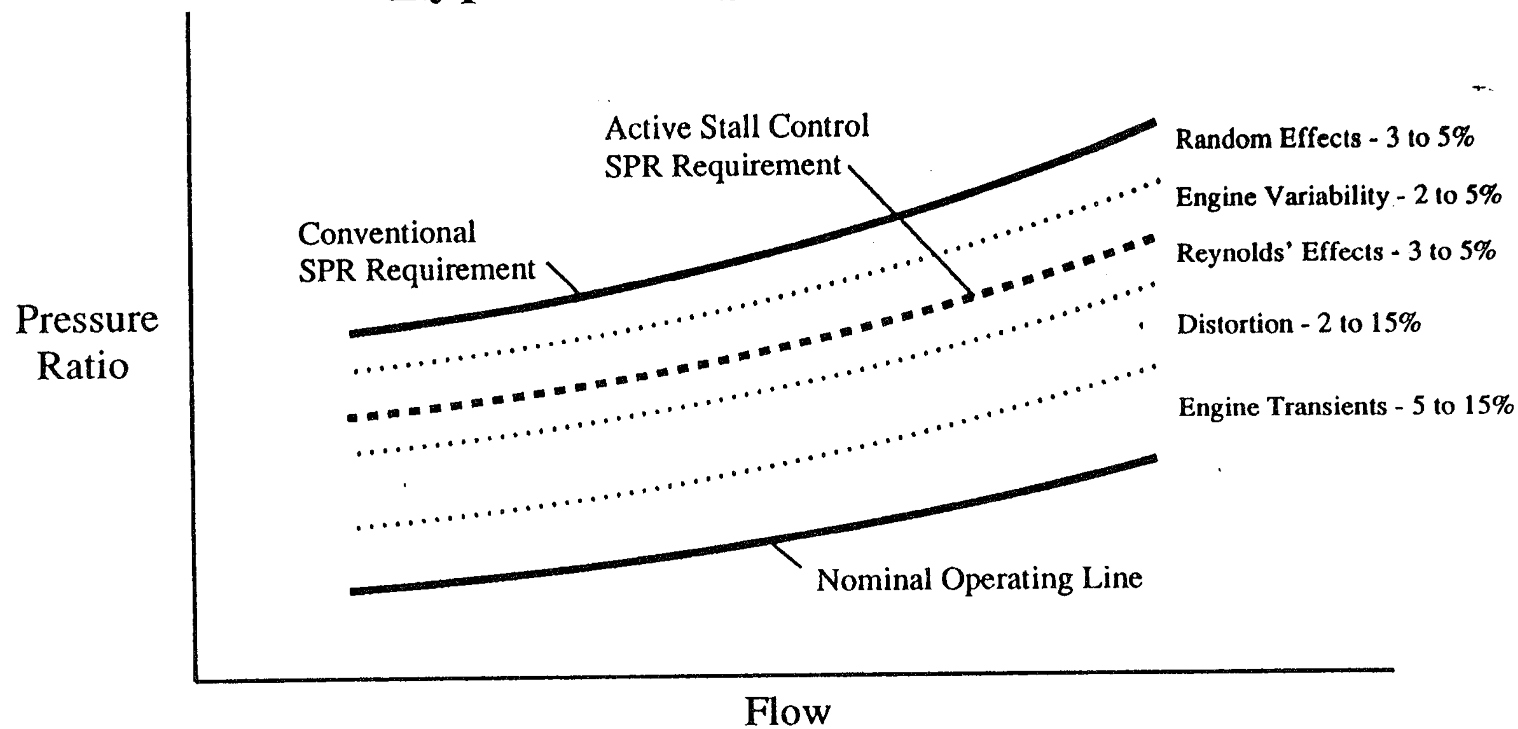
Improved system modeling capability.

G. W. Gallops
Pratt & Whitney GESP
January 27, 1992

ASC Challenge

Eliminate SPR requirements related to uncertainty by augmenting aerodynamic and engine system stability in the near stall operating regime.

Typical Compressor Requirements



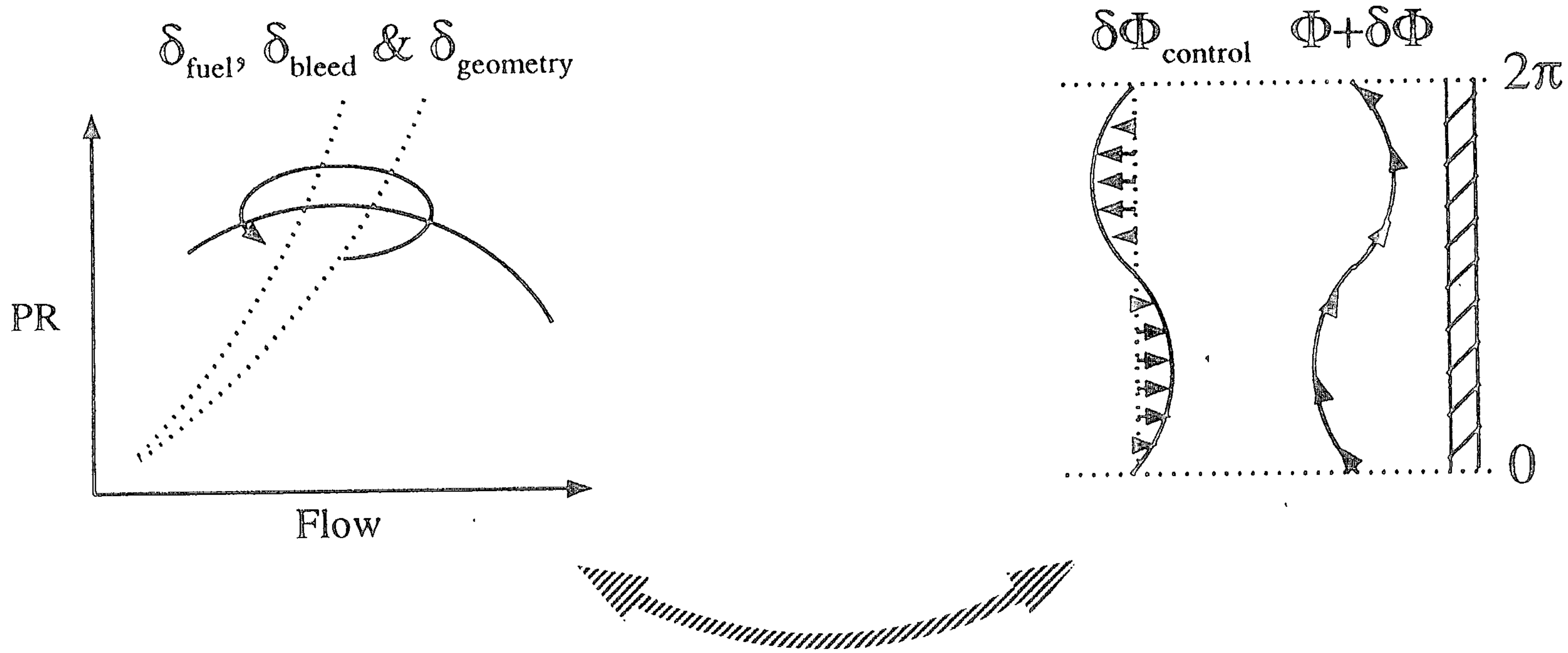
G. W. Gallops
Pratt & Whitney GESP
January 27, 1992

ASC Approach

Stability augmentation requires consideration of the engine system dynamics, compression system aerodynamics and their interactions.

System Stability

Aerodynamic Stability



Interactions

G. W. Gallops
Pratt & Whitney GESP
January 27, 1992

Obstacles to ASC Implementation

Physics

Understanding full engine stall inception phenomena.
Understanding system forced response to ASC effectors.
Controllability of combustion process.

Hardware

Light–weight, reliable high response sensors and actuators.
(State-of-the-art control processors are adequate.)

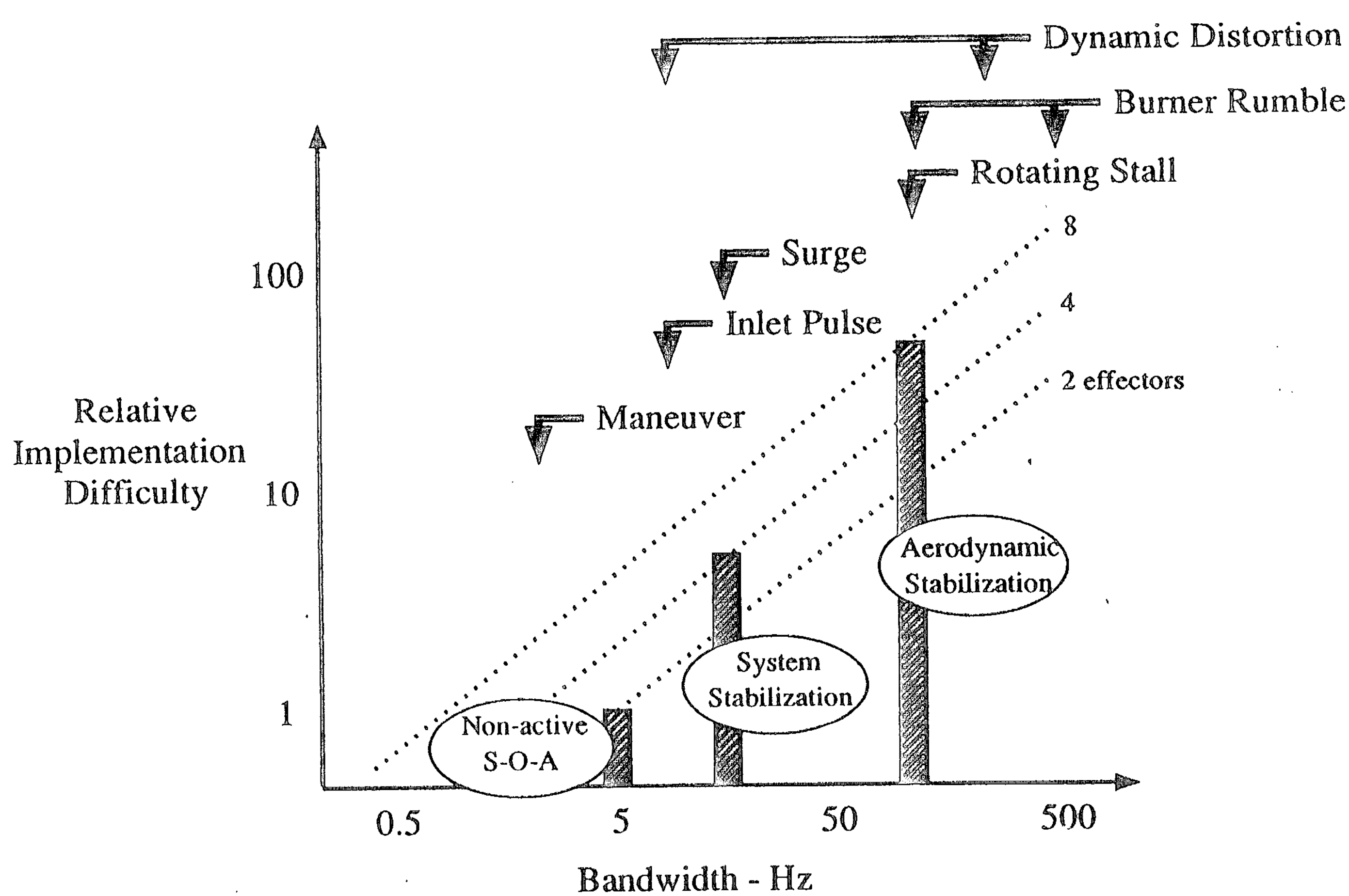
Programatics

Inter-discipline communication.
Manufacturer acceptance & funding.
Customer Acceptance.

G. W. Gallops
Pratt & Whitney GESP
January 27, 1992

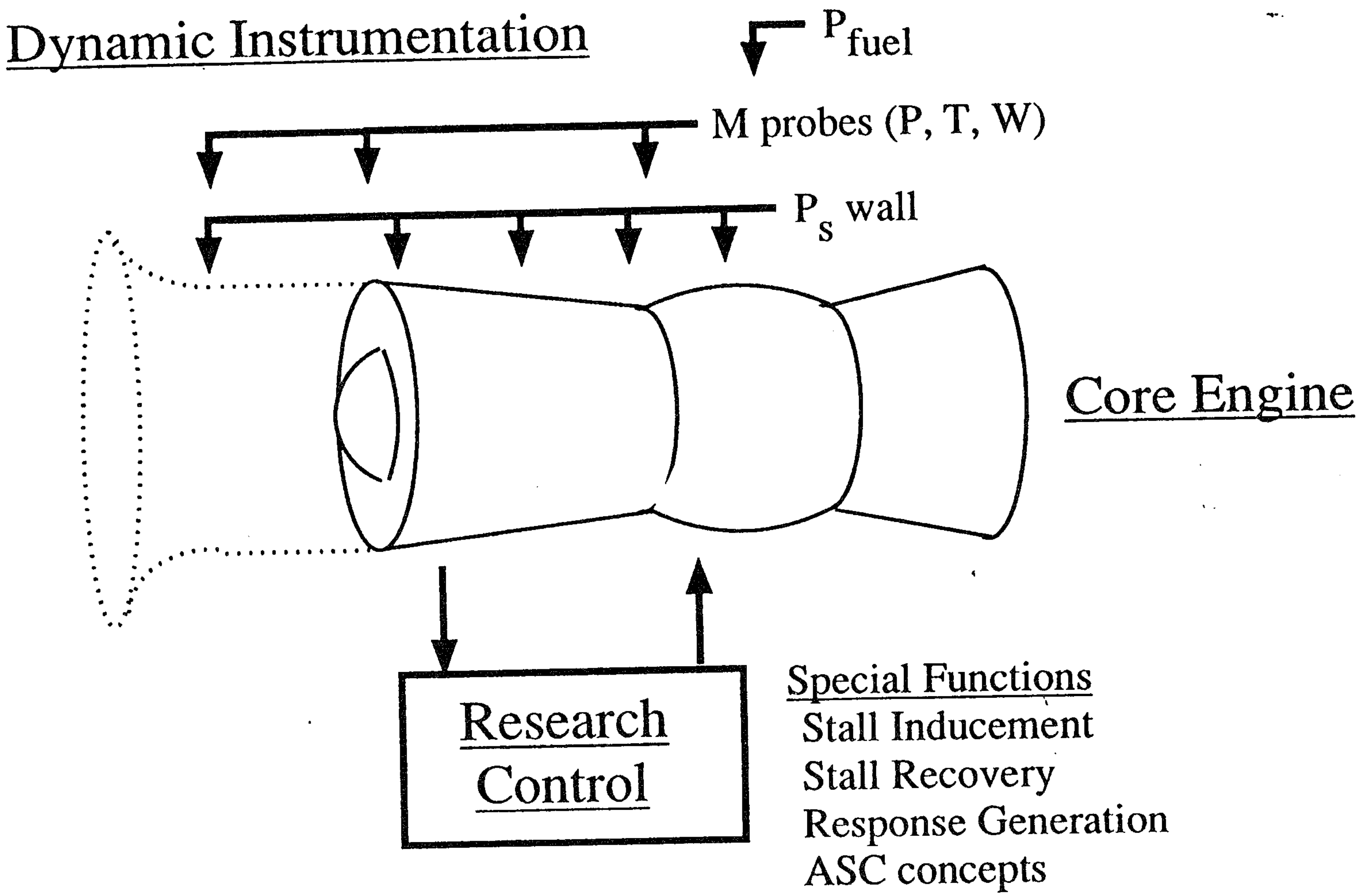
Active Control Hardware Requirements

ASC implementation will possibly require capabilies ten times better than current state-of-the-art.



G. W. Gallops
Pratt & Whitney GESP
January 27, 1992

Core Research Environment



G. W. Gallops
Pratt & Whitney GESP
January 27, 1992

Stall testing and Analysis of Two Mixed Flow Turbofans

G. W. Gallops, T. J. Roadinger and J. V. French
Pratt & Whitney GESP
West Palm Beach FL

The 38th ASME International Gas Turbine & Aeroengine Congress
Cincinnati OH - May 27, 1993

Acknowledgments

APL sponsored program to develop and validate high frequency in-stall model methodology (1980 - 84).

USAF Aero Propulsion Laboratory

H. R. Bankhead
M. F. Schmidt

USAF Arnold Engineering Develoment Center

G. T. Patterson
A. E. Burwell

Pratt & Whitney

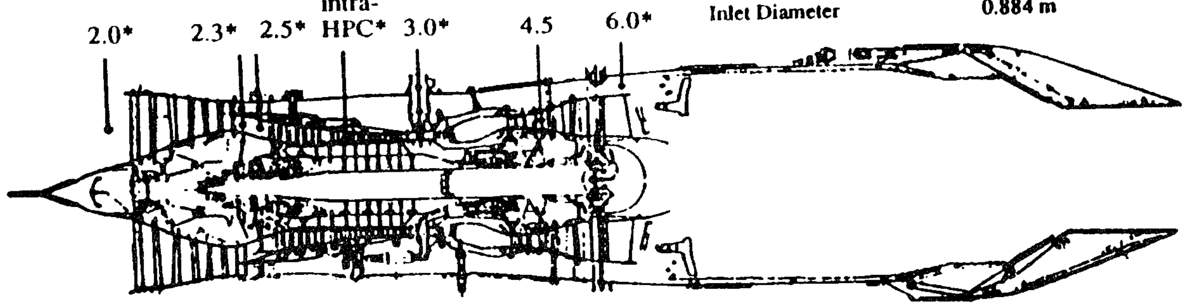
J. V. French
A. B. Cady

Test Engine Configurations

Emphasis on aerodynamic and system dynamic interaction.

Moderate BPR Configuration

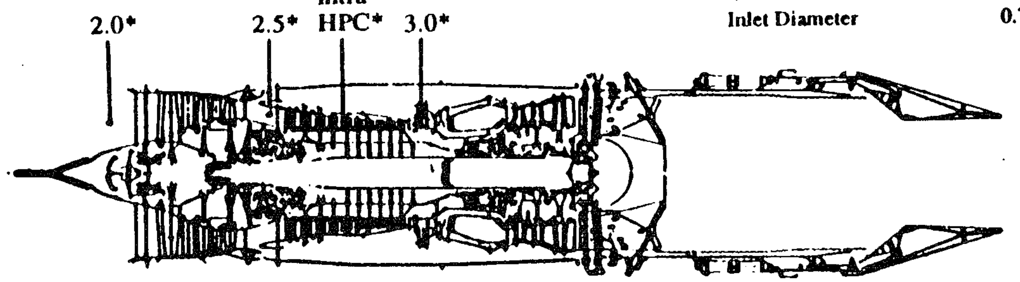
Dynamic Instrumentation Locations
* Mach Probes



Thrust	104.3 kN (23.4 klb) afterburner 63.9 kN (14.4 klb) non-afterburner
Bypass Ratio	0.60
Overall Pressure Ratio	25
Inlet Diameter	0.884 m

Low BPR Configuration

Dynamic Instrumentation Locations
* Mach Probes

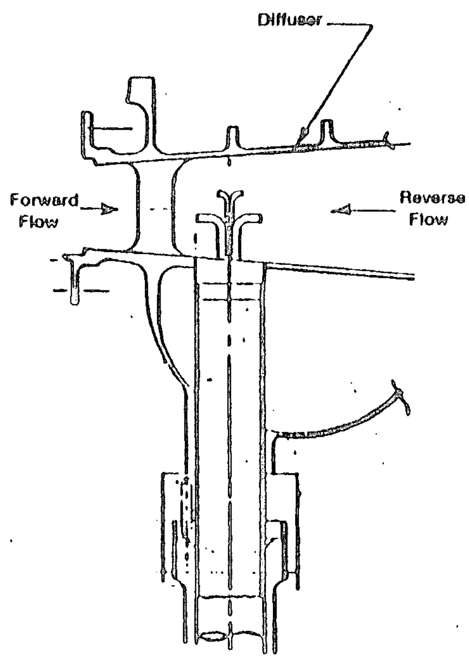


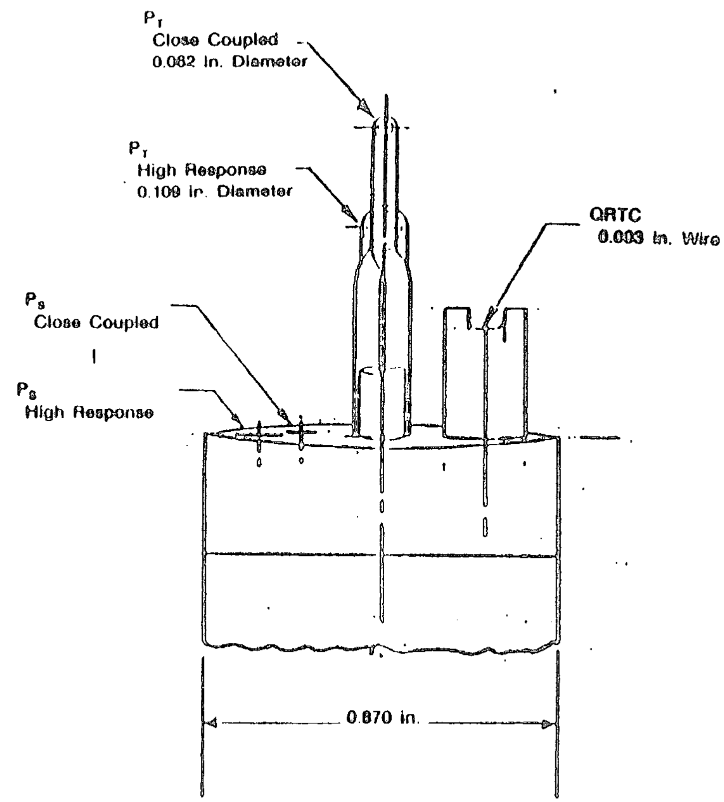
Thrust	91.7 kN (20.6 klb) afterburner 60.4 kN (13.6 klb) non-afterburner
Bypass Ratio	0.22
Overall Pressure Ratio	25
Inlet Diameter	0.777 m

G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

Mach Probes

Local pressure, temperature and flow; response above 250 Hz.





G. W. Gallops
Pratt & Whitney GESP

May 27, 1993

Installation & Test Procedures

Represent as many aspects of operational environment as practical.

Representative Installation: inlet, bleed & power extractions

Flight Conditions: 0.8 Mach / 15 kft to 45 kft

Stall Inducement: control schedules, throttle movements

Disabled Stall Avoidance & Recovery Functions

G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

Test Results

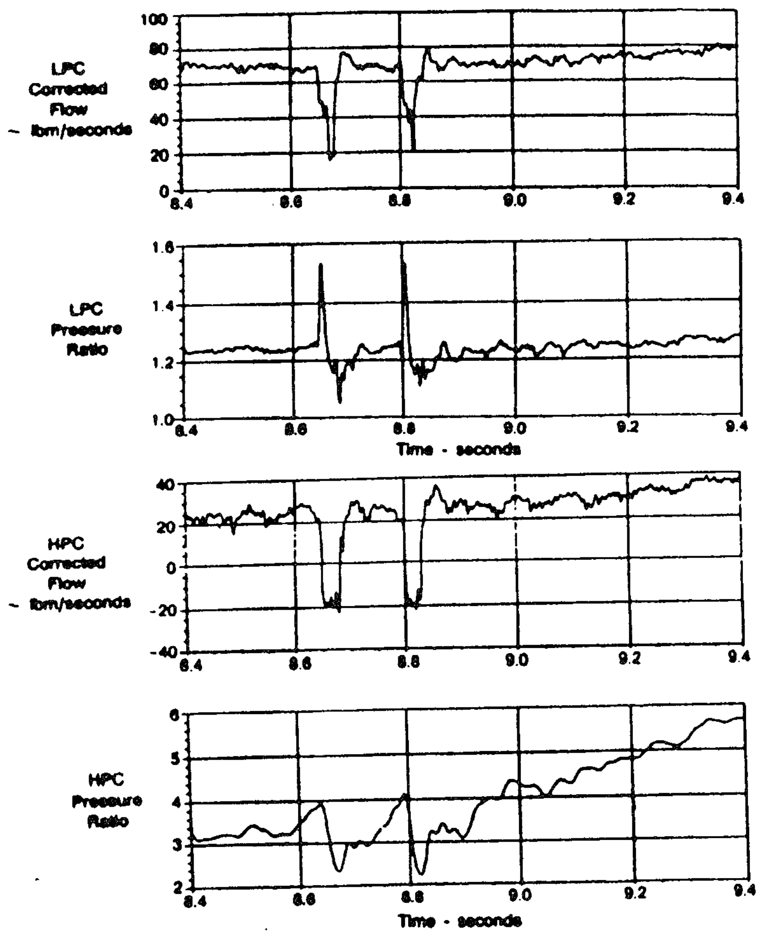
HPC Acceleration Stalls

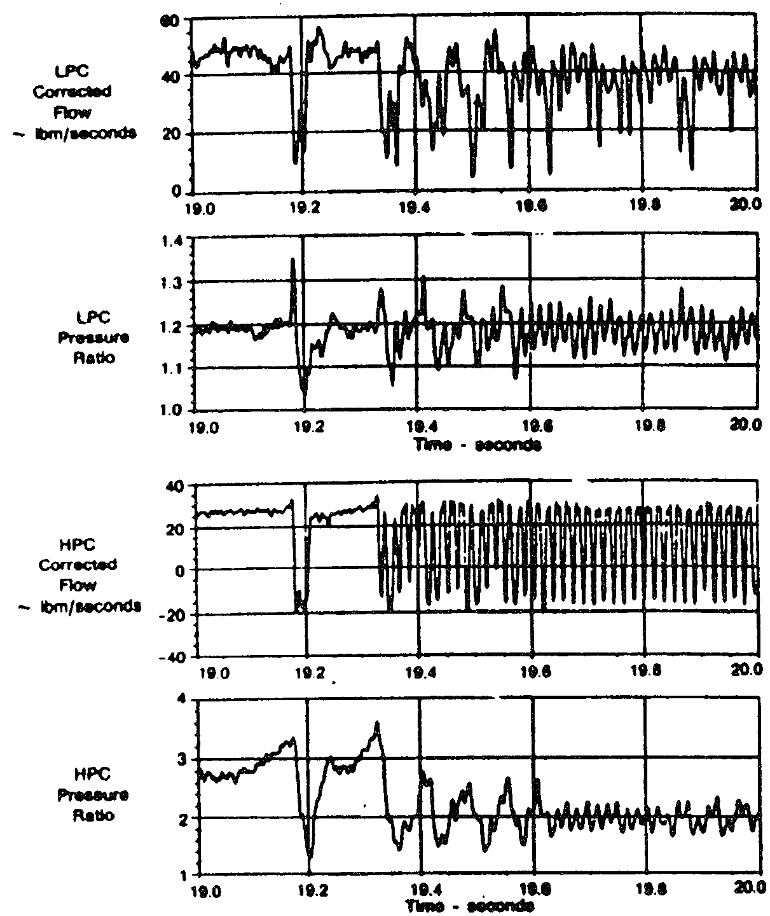
LPC Deceleration Stalls

Fan & LPC High Power Stalls

Component In-Stall Characteristics

HPC Acceleration Stalls

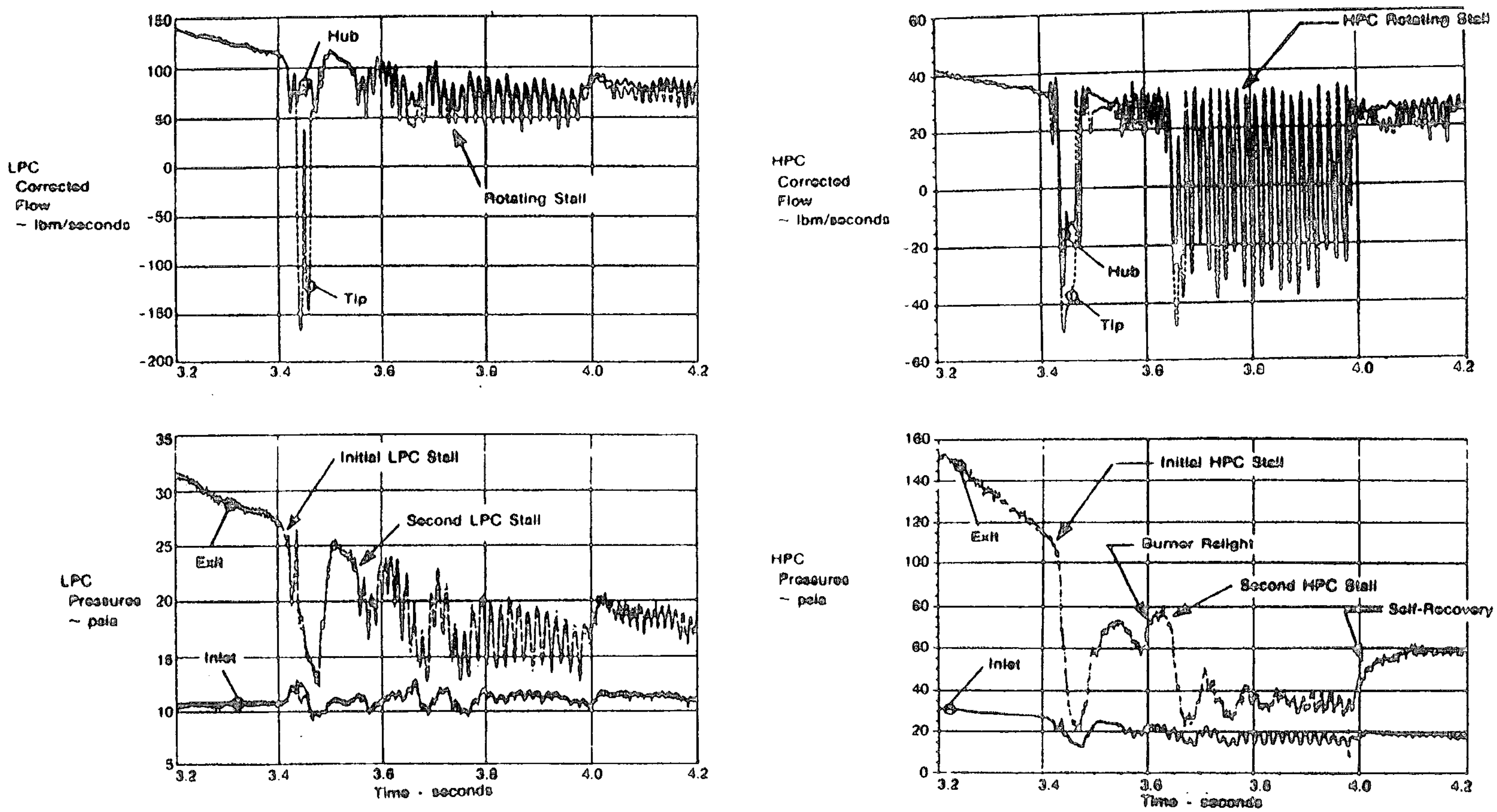




G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

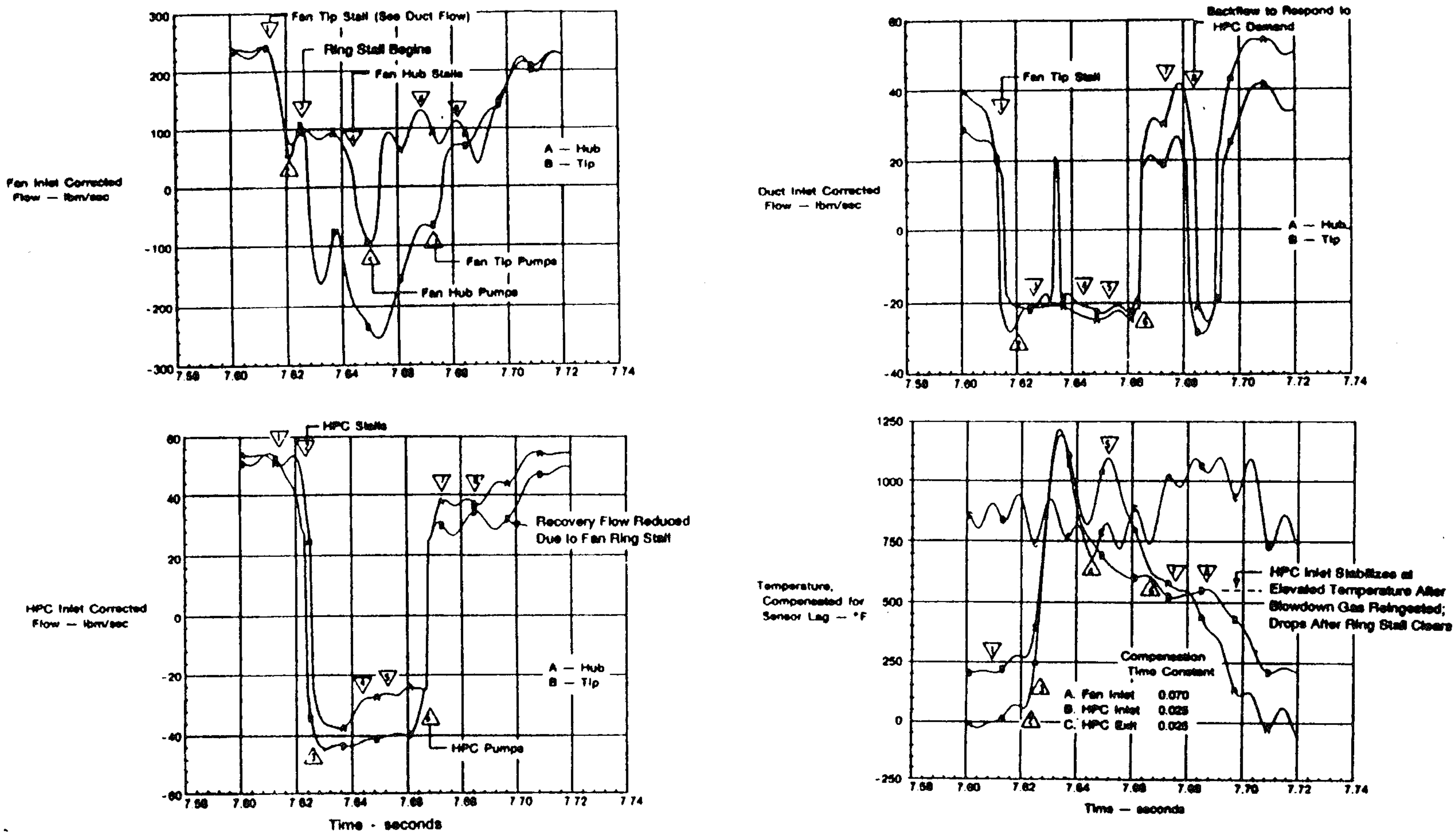
7

LPC Deceleration Stall



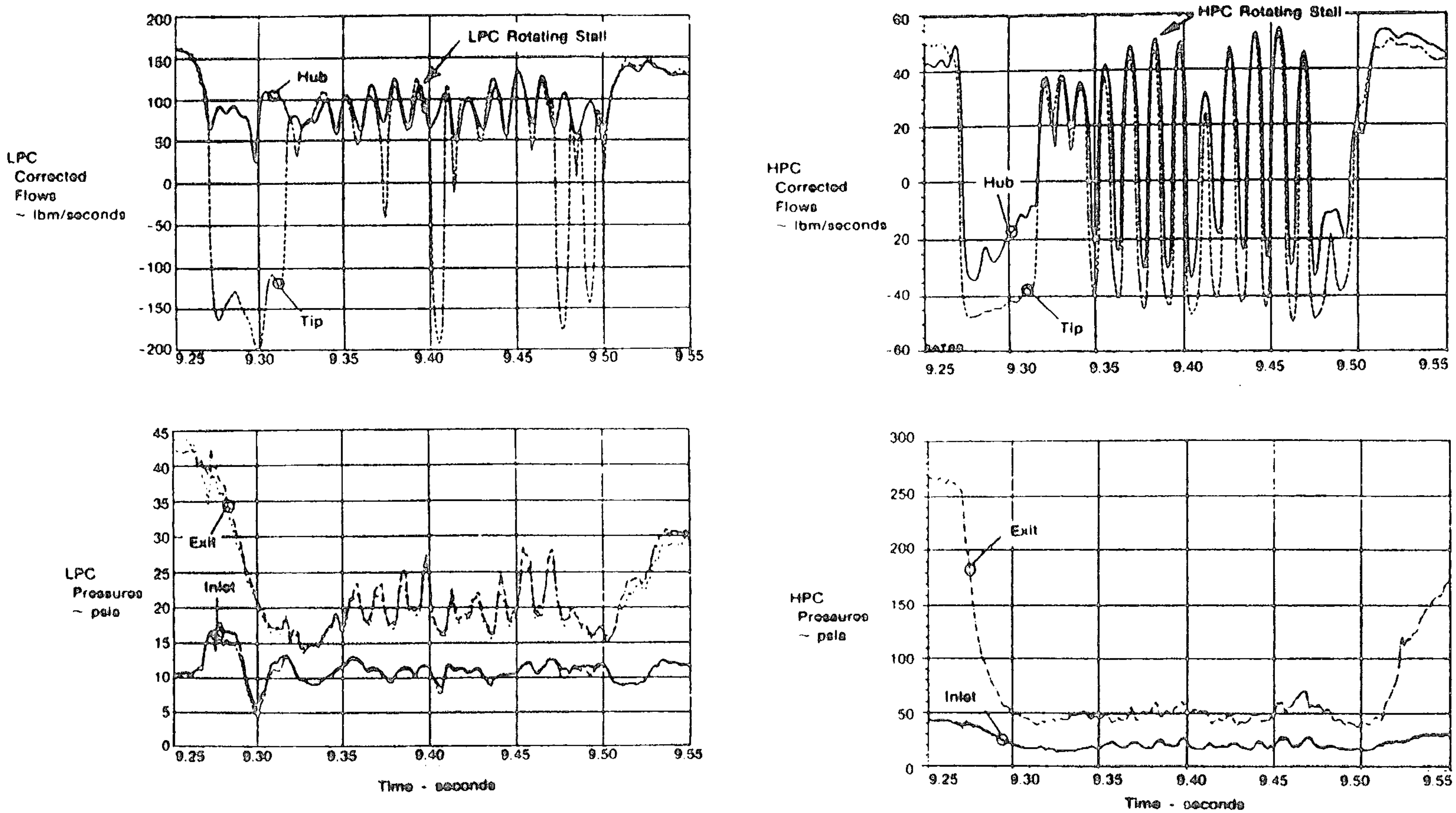
G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

High Power Fan Stall



G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

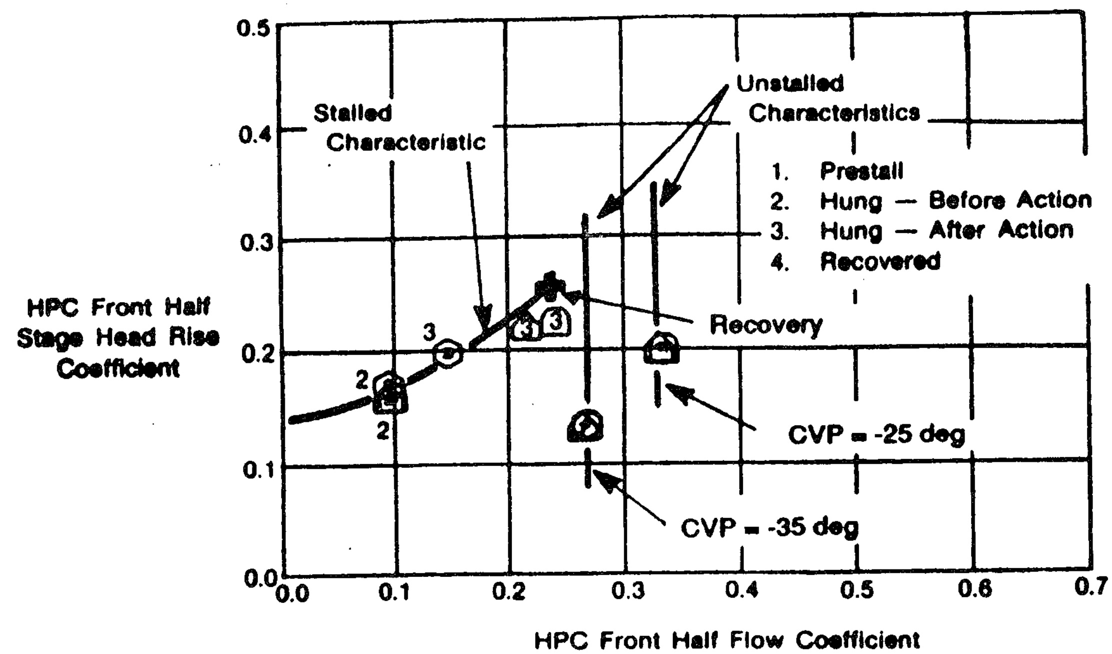
High Power LPC Stall with Delayed Recovery



G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

10

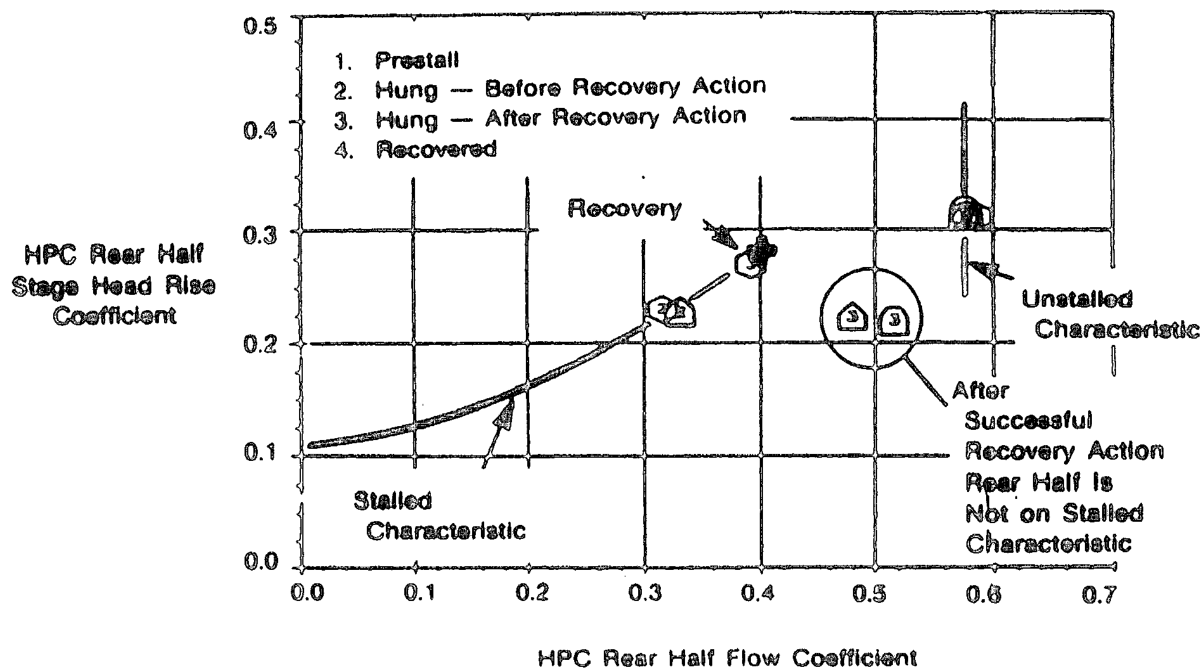
Front HPC In-Stall Characteristic



G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

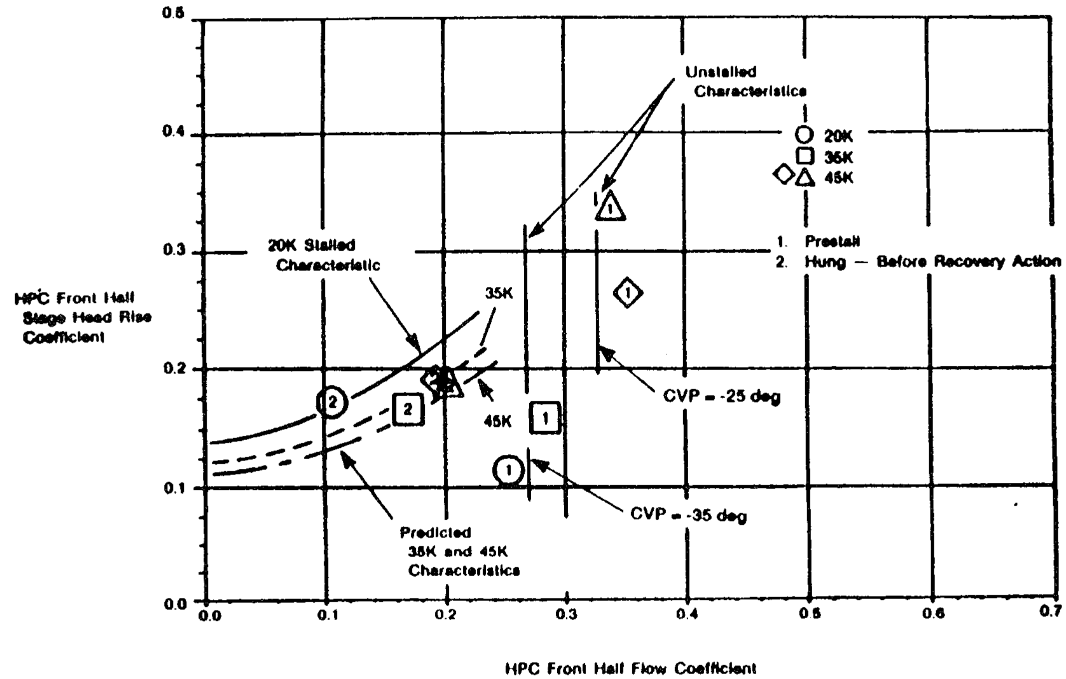
11

Rear HPC In-Stall Characteristic



G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

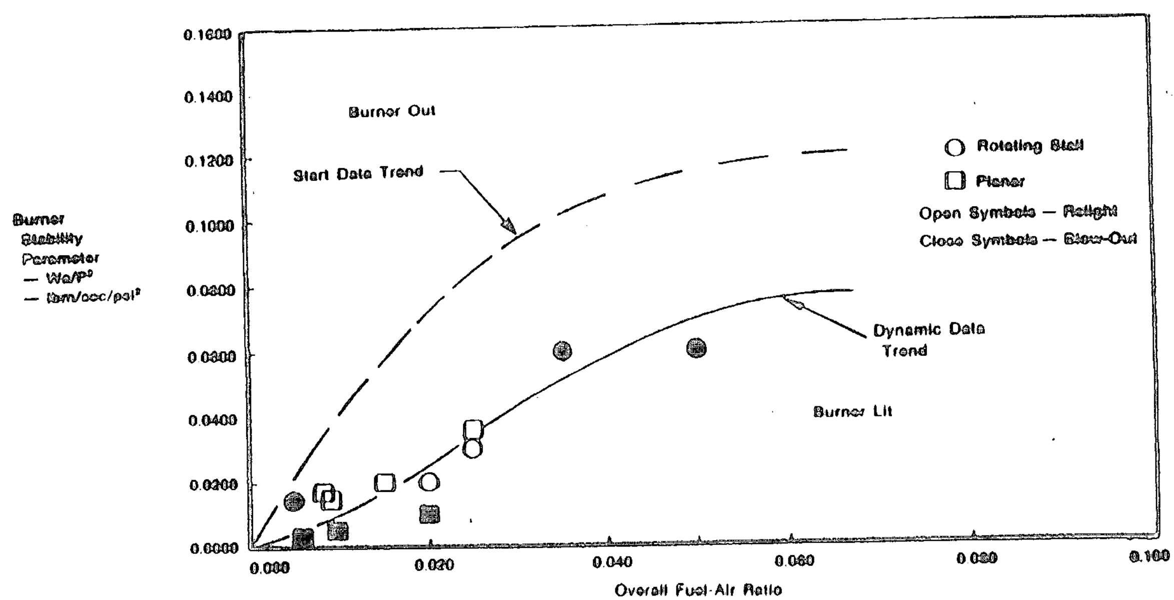
Reynolds' Effects on HPC In-Stall Characteristic



G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

13

Burner In-Stall Stability Limit



G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

14

Summary

Effective test and analysis of stall inception and recovery phenomena can be performed in a full engine environment.

Engine test results generally support component test and analytical results.

Component aerodynamic and system dynamic interactions can dominate stall inception and recovery processes.

G. W. Gallops
Pratt & Whitney GESP
May 27, 1993

ACTIVE CONTROL USING ACOUSTICALLY ACTIVE SURFACES

Sumon K. Sinha
University of Mississippi
Mechanical Engineering Dept.
University, MS 38677
Ph: 601-232-5374
Fax: 601-232-7219

WINCAT

Possible Uses

1. Active Noise Control

2. Active Control of Unsteady Flow Separation

3. Active Control of Structural Dynamics/Aeromechanics

4. Active Control of Heat Transfer

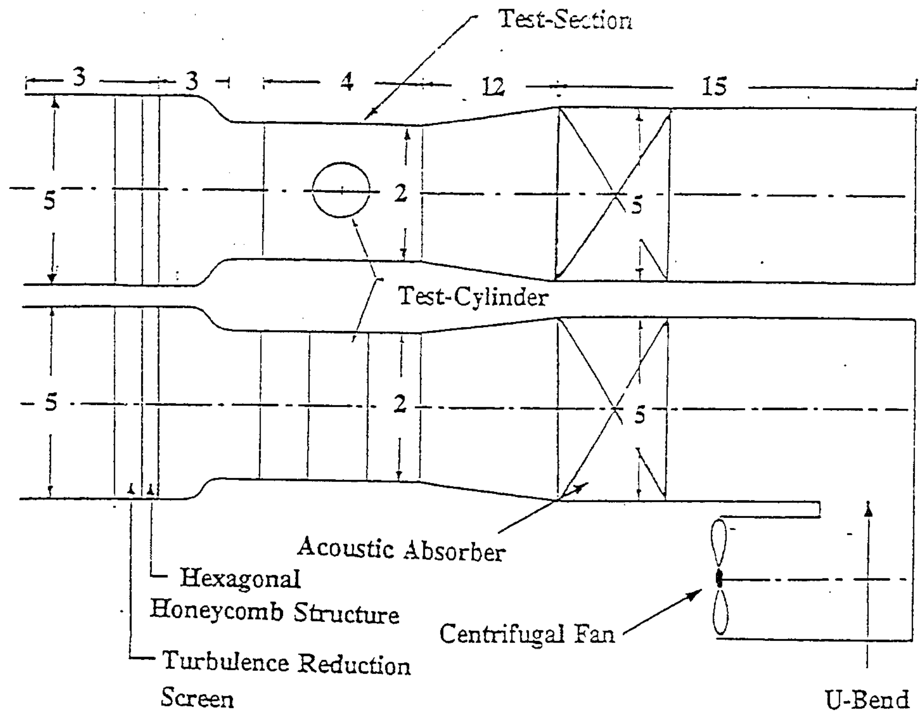
Processes are Inter-Related

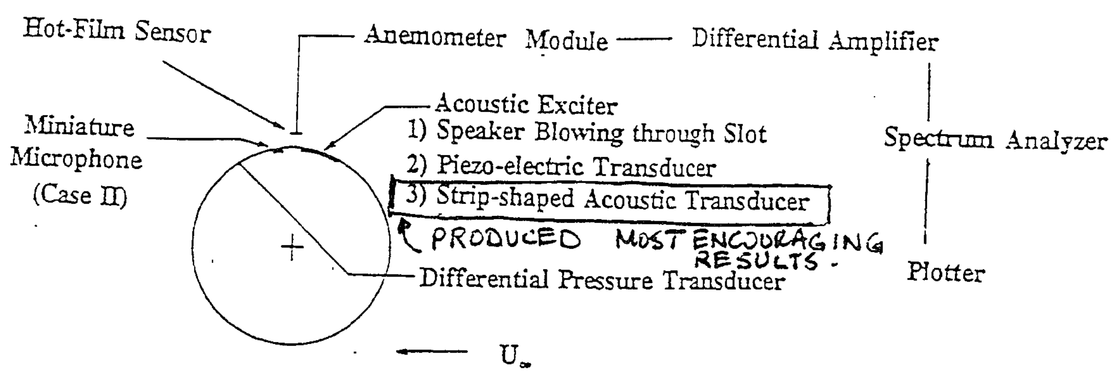
MOTIVATION

CONTROLLING UNSTEADY FLOW SEPARATION OPTIMALLY

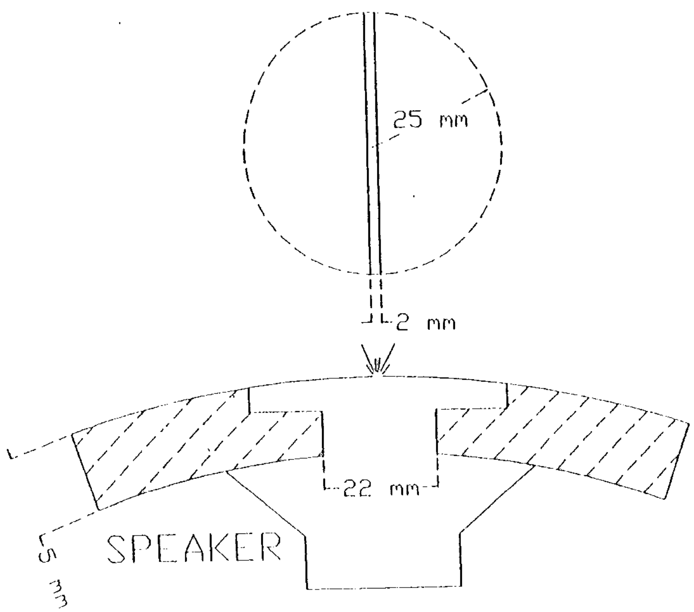
DEVELOPING A MECHANICALLY SIMPLE ACTUATOR FOR POSSIBLE USE ON COMPRESSOR BLADES AND HELICOPTER ROTORS.
ACOUSTIC TRANSDUCERS ARE MECHANICALLY UNCOMPLICATED

UNDERSTANDING HOW AN ACOUSTIC ACTUATOR INTERACTS WITH THE FLOW TO OPTIMIZE ACTUATOR DESIGN AND CONTROL STRATEGY

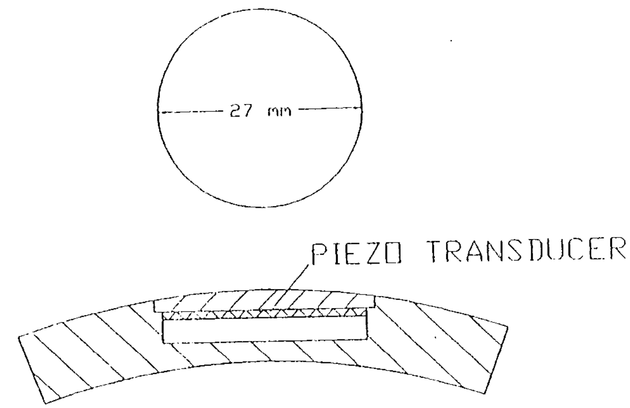




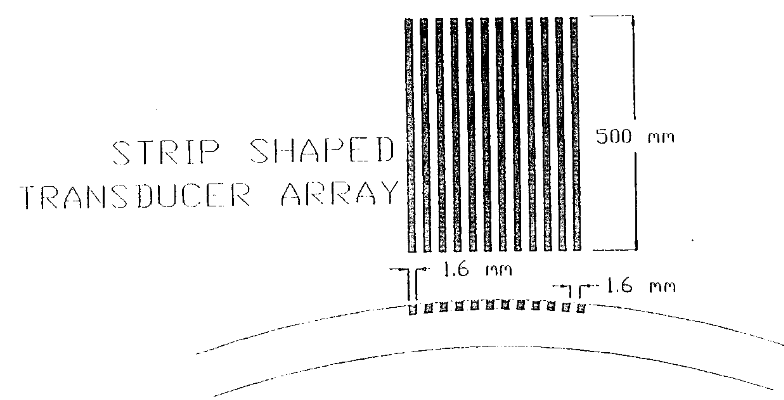
Construction details of the wind-tunnel testing facility. All dimensions in ft.
(Not to scale)



SPEAKER-SLOT EXCITATION

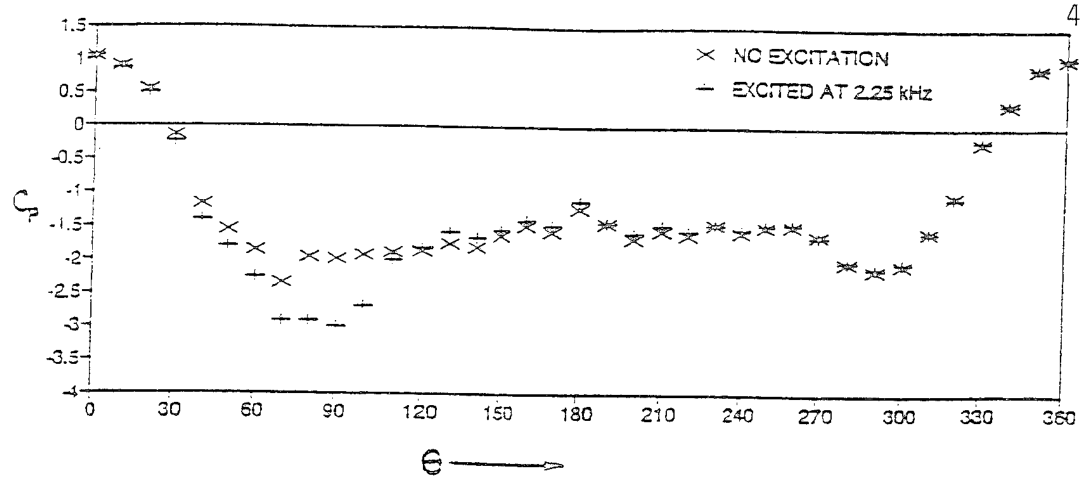


PIEZO TRANSDUCER EXCITATION



STRIP EXCITATION

FEATURE	SPEAKER/SLOT EXCITER	CIRCULAR PIEZO EXCITER	STRIP ARRAY EXCITER
PERTURBATION CHARACERISTICS	ACOUSTIC RADIATION; BLOWING-SUCTION VELOCITIES COMPARABLE TO FREE STREAM. NOMINALLY 2-D PERTURBATION	PURE ACOUSTIC RADIATION; NEGLIGIBLE NORMAL VELOCITIES AT SURFACE. COMPLEX 3-D PERTURBATION	PURE ACOUSTIC RADIATION; NEGLIGIBLE NORMAL VELOCITIES AT SURFACE. NOMINALLY 2-D PERTURBATION
EFFECTIVE FREQUENCY RANGE FOR CONTROL	400 - 700 Hz	5 - 7 kHz	2.25 kHz
FLOW REYNOLDS NO. RANGES WHERE CONTROL IS POSSIBLE	FROM 6000 (LAMINAR) TO 1.5×10^5 (TRANSITION)	1.4×10^5 TO 1.6×10^5 (LAMINAR, TRANSITIONAL)	1.4×10^5 TO 1.6×10^5 (TRANSITIONAL AND TRIPPED)
POWER REQUIREMENTS	HIGHEST; CONTROL RANGE AND EFFECTIVENESS CAN BE EXTENDED BY INCREASING POWER INPUT	NEGLIGIBLE; MINIMUM SPL NEEDED (90 dB); INCREASING SPL DOES NOT HELP IN IMPROVING CONTROL	NEGLIGIBLE; MINIMUM SPL NEEDED (75 dB); INCREASING SPL DOES NOT HELP IN IMPROVING CONTROL
OPTIMUM EXCITATION LOCATION	UNEXCITED MEAN LAMINAR SEPARATION POINT	UNEXCITED MEAN LAMINAR SEPARATION POINT	UPSTREAM OF UNEXCITED MEAN LAMINAR SEPARATION POINT (EVEN FOR TRIPPED FLOW)
MEAN SURFACE PRESSURES	DECREASE AROUND POINT OF EXCITATION	INCREASE AROUND POINT OF EXCITATION	DECREASE AROUND POINT OF EXCITATION (UNTRIPPED); ALSO INCREASE IN WAKE (TRIPPED)
VELOCITY FLUCTUATIONS	INCREASE	DECREASE	DECREASE
FORM DRAG	REDUCES ??	INCREASES ??	DECREASES BY 10 TO 20%

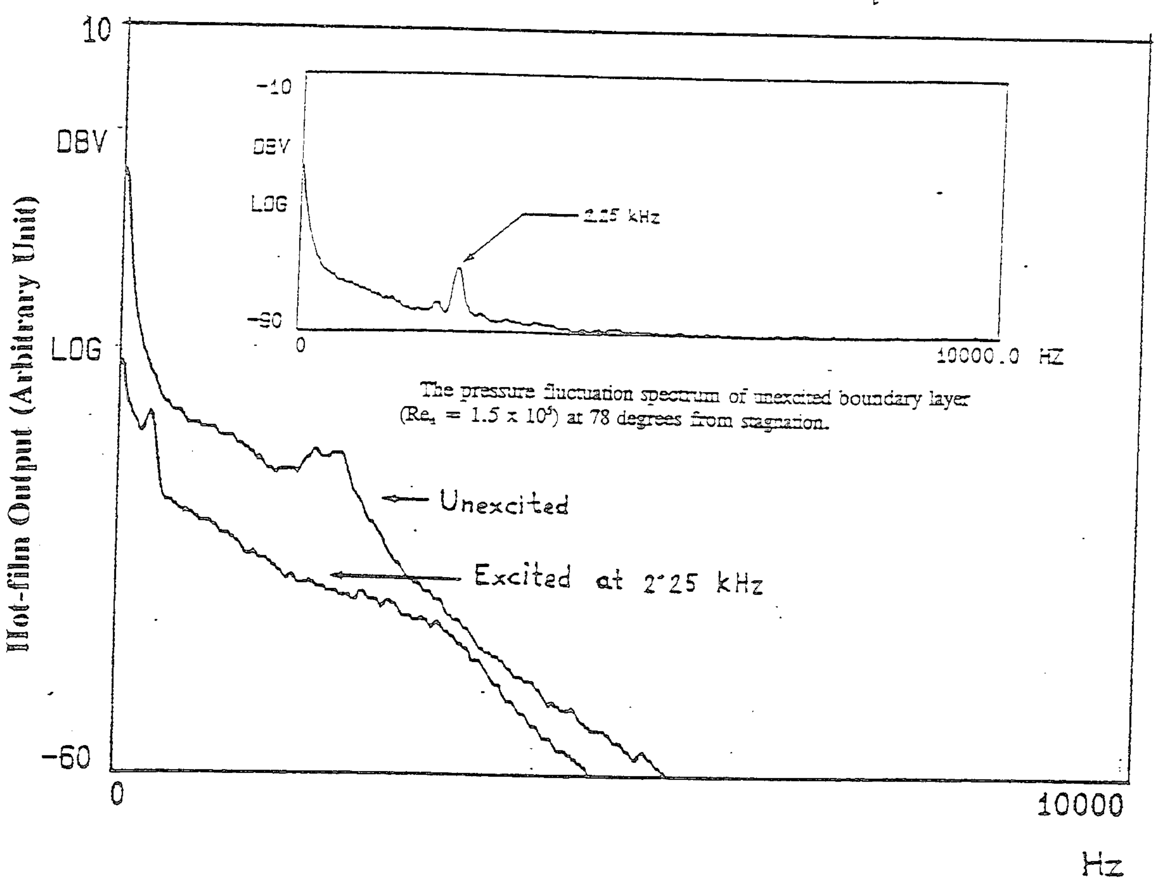


Surface static pressure distribution (unexcited and excited flow states). $Re_d = 1.5 \times 10^5$. $f_s = 2.25$ kHz. Location of excitation : $\Theta = 72°$-$74°$ (multiple strip excitation).

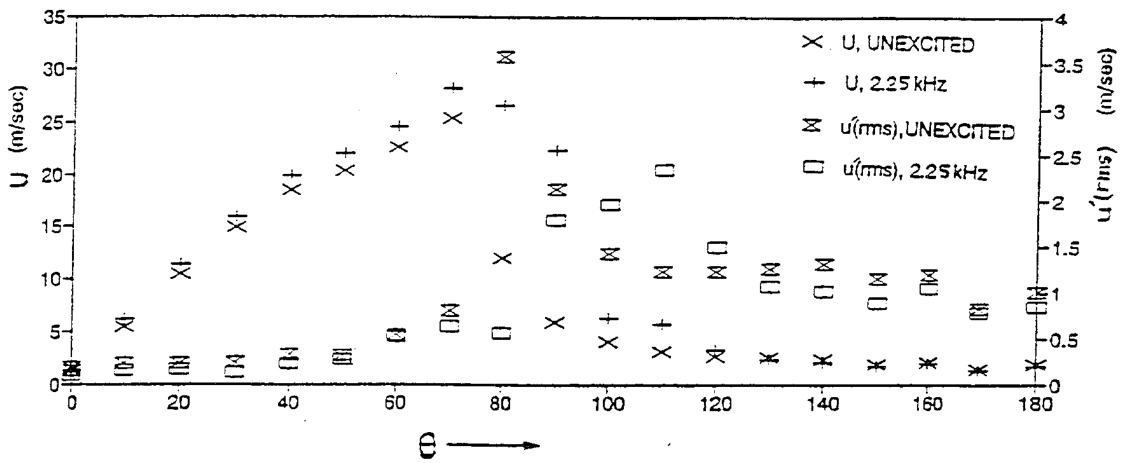
C_L (UNEXCITED) = 0.15

C_L (EXCITED) = 0.47

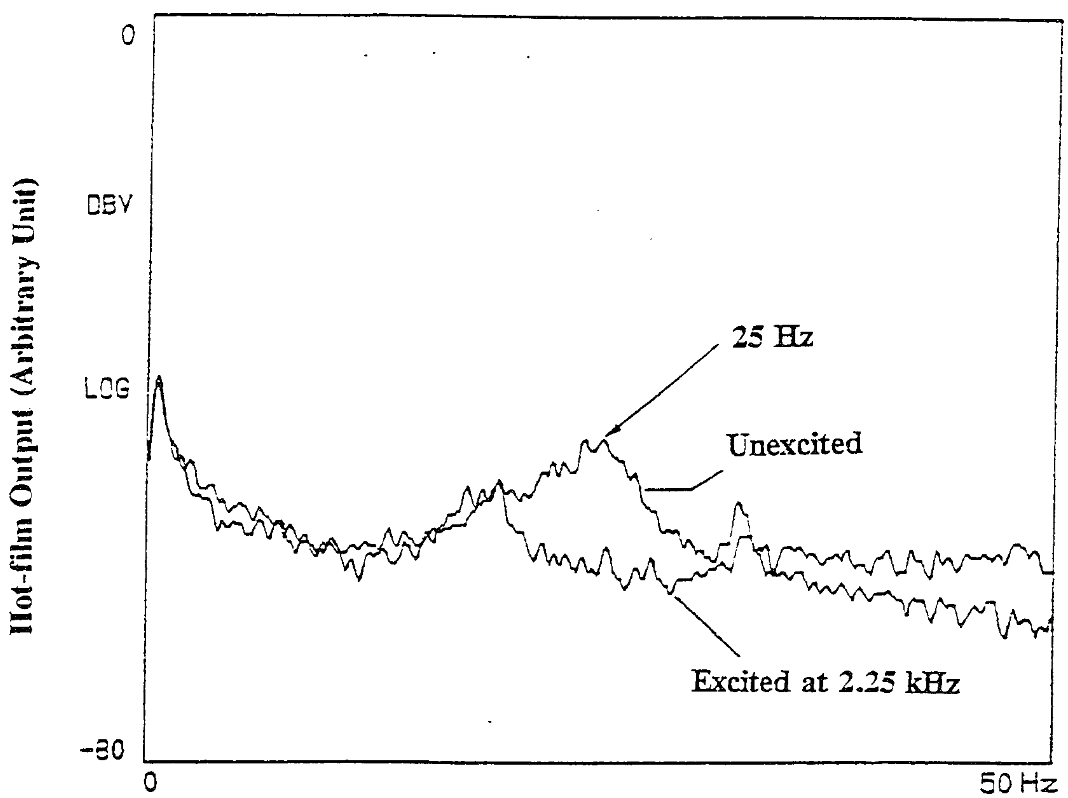
FORM-DRAG REDUCTION = 12.4 %



Time averaged velocity spectra of post-separation shear layer. $Re_d = 1.5 \times 10^5$. $f_s = 2.25$ kHz.
Excitation location : $\Theta = 72°$-$74°$ (multiple strip excitation).
Measurement location : $\Theta = 82°$, y = 8-mm.

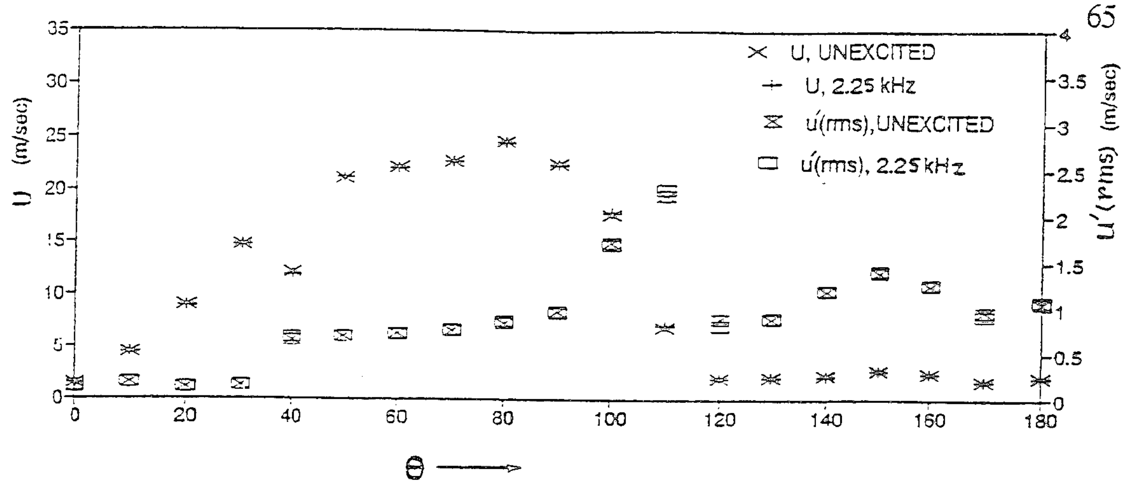


Distribution of time-averaged mean and fluctuation velocities close to the cylinder surface. y = 1-mm for all measurement locations.
$Re_d = 1.5 \times 10^5$. and $f_a = 2.25$ kHz.
Excitation location : $\Theta = 72°$-$74°$ (multiple strip excitation).

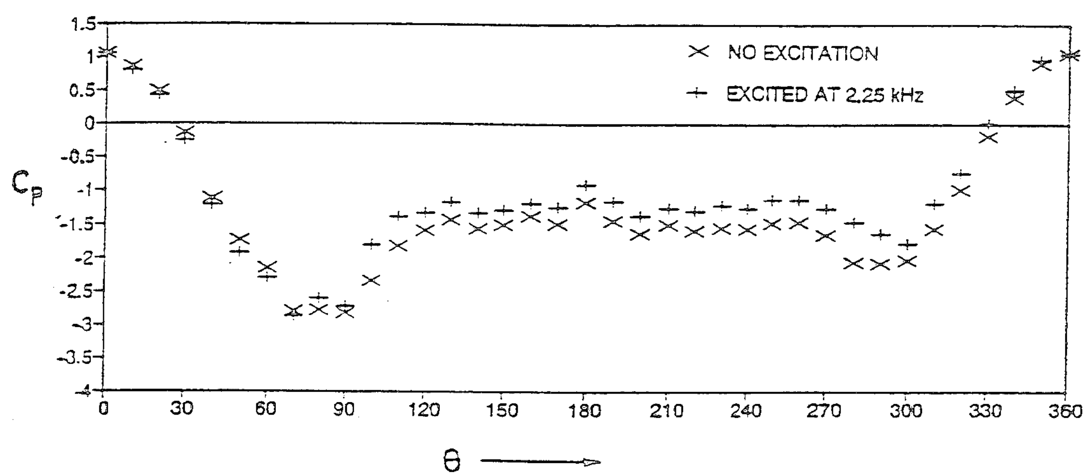


Velocity spectra of cylinder wake under unexcited and excited states. Output signal from channel A of two-component velocity probe. Prominent peak at 25 Hz under unexcited flow conditions. $f_a = 2.25$ kHz. $Re_d = 1.5 \times 10^5$.
Location of excitation : $\Theta = 72°$-$74°$.
Measurement location : $\Theta = 110°$, y = 10-mm.

65



Distribution of time-averaged mean and fluctuation velocities close to the cylinder surface. y = 1-mm for all measurement locations. $Re_d = 1.5 \times 10^5$. $f_a = 2.25$ kHz.
Artificial flow tripping at Θ = 35°.
Excitation location : Θ = 92°-94° (multiple strip excitation).



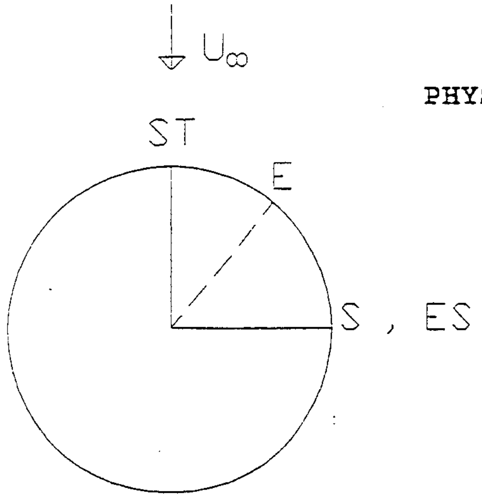
Surface static pressure distribution (unexcited and excited flow states). $Re_d = 1.5 \times 10^5$. $f_a = 2.25$ kHz.
Artificial flow tripping at Θ = 35°.
Location of excitation : Θ = 72°-74° (multiple strip excitation).

C_L (UNEXCITED) = 0.33

C_L (EXCITED) = 0.54

FORM-DRAG REDUCTION = 20.2%.

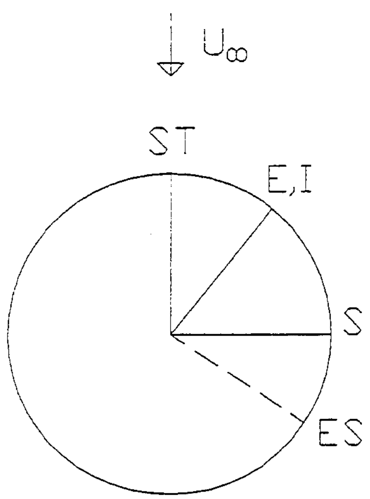
PHYSICAL EXPLANATION OF PHENOMENA



Low-Re; Stable Laminar Flow

<u>Unexcited</u>: Flow separates at S before attaining critical Re for disturbance amplification

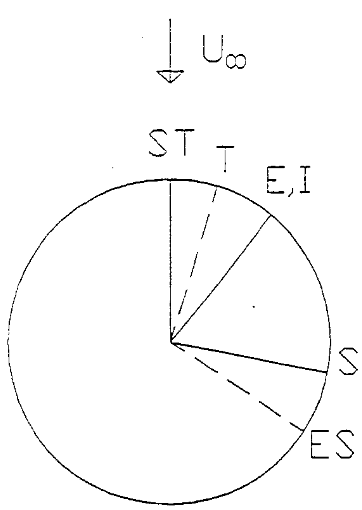
<u>Excited</u>: Acoustic excitation at any point E between ST and S gets attenuated downstream. Extremely large amplitudes needed for control.



Higher-Re; Transitional Flow

<u>Unexcited</u>: Flow reaches critical Re at point I. However, naturally occurring disturbances cannot amplify adequately to delay separation.

<u>Excited</u>: Acoustic excitations at E above the threshold of natural disturbances can reduce transition length and delay separation. Most effective if E and I coincide.



Transitional flow tripped at T to become turbulent

<u>Unexcited</u>: Large amplitude disturbances at T reduce transition length sufficiently to delay separation.

<u>Excited</u>: Small amplitude acoustic excitations are most effective if introduced at I. Modifies the non-linear amplification process.

ST - Mean Stagnation Point
I - Instability Point
S - Mean Separation Point (Unexcited)
ES - Mean Separation Point (Excited)
E - Point of Excitation
T - Point of Tripping

Research Needs

1. Actuator/Sensor development

2. Understanding interaction with flow, acoustic field, thermal field, and vibrational amplitudes and modes

3. Control hardware/software and algorithm development

HEAT TRANSFER and MEASUREMENTS

<u>WINCAT Workshop</u>

Purdue University, October 4-6, 1993

Robert J. Simoneau
Chief, Heat Transfer Branch
NASA Lewis Research Center

21000 Brookpark Road, Cleveland, OH 44135-3191
Phone: (216) 433-5883; FAX: (216) 433-3000

****

NASA

Lewis Research Center

Heat Transfer and Measurements

THEME/ISSUES

- Simultaneous (Matched) Aero/Heat Transfer Exp
- Comparable Aero/Heat Transfer Measurement Fidelity
- Assessment of Instantaneous vs. Average Effects

Heat Transfer and Measurements

SIMULTANEOUS AREO/HEAT TRANSFER

EXP TYPE	*AVG TIME*	*AERO MEAS*	*HT MEAS*
Shock Tunnel	20 msec	Poor	Very Good
Light Piston	100 msec	Inadequate	Very Good
Blowdown	500 msec	Good	Very Good
Steady	All day	Excellent	Fair

Heat Transfer and Measurements

COMPARABLE MEASUREMENT FIDELITY

- Short Duration Experiments
  - Heat Transfer - Thin Film Sensors
    - Strengths: Fast, Non-Intrusive, High Accuracy
    - Weakness: Limited Resolution
  - Aero - Particle Image Velocimetry
    - Strengths: Fast, High Resolution
    - Weakness: Expensive, Complex

- Steady Running Experiments
  - Heat Transfer - Heat Flux Gages
    - Weaknesses: Intrusive, Limited Resolution, Limited Accuracy, Slow
  - Aero - Laser Doppler Velocimetry, Hot Wire
    - Strengths: Fast, Non-Intrusive, High Resolution

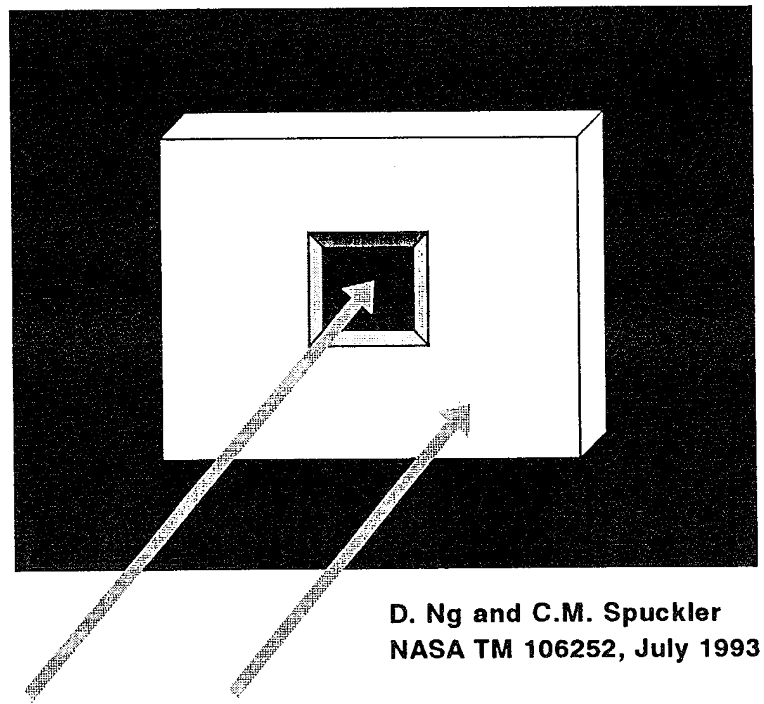
- New Heat Transfer Measurement Potential
  - Laser Induced Fluorescence/Thermographic Phosphors
  - Multi-Wavelength Pyrometry/Semi-Transparent Media

Heat Transfer and Measurements

NON-CONTACT HEAT FLUX MEASUREMENT USING A TRANSPARENT SENSOR

Key Features of Experiment:

- 8 mm Shappire Crystal
- Back Surface Graphite Paint
- Black Body Source at 950 to 1250 K
- Multi-Wavelength Pyrometer



Material Transparent at Short Wavelenghts Yielding: Subtrate Temperature

Material Opaque at Long Wavelengths Yielding: Surface Temperature

D. Ng and C.M. Spuckler
NASA TM 106252, July 1993

Results:

Heat Flux Measured to Within 2.5% Without Calibration

NASA

WINCAT08

Lewis Research Center

Heat Transfer and Measurements

NON-CONTACT HEAT FLUX MEASURMENT USING A TRANSPARENT SENSOR

NEXT STEPS

√ Repeat baseline experiment with polycrystalline alumina
- Transmissity/Emissity properties comparable but not as sharp and definitive as with shappire

√ Experiment with flame spayed alumina and zirconium oxide, sprayed on a metal base
- Radiation transmissity properties unknown
- Calibration technique required
- Validation experiment more complex

√ Move technique to time accurate, real environment
- Develop scanning mulit-wavlength pyrometer
- Develop data reduction software, based on step 2

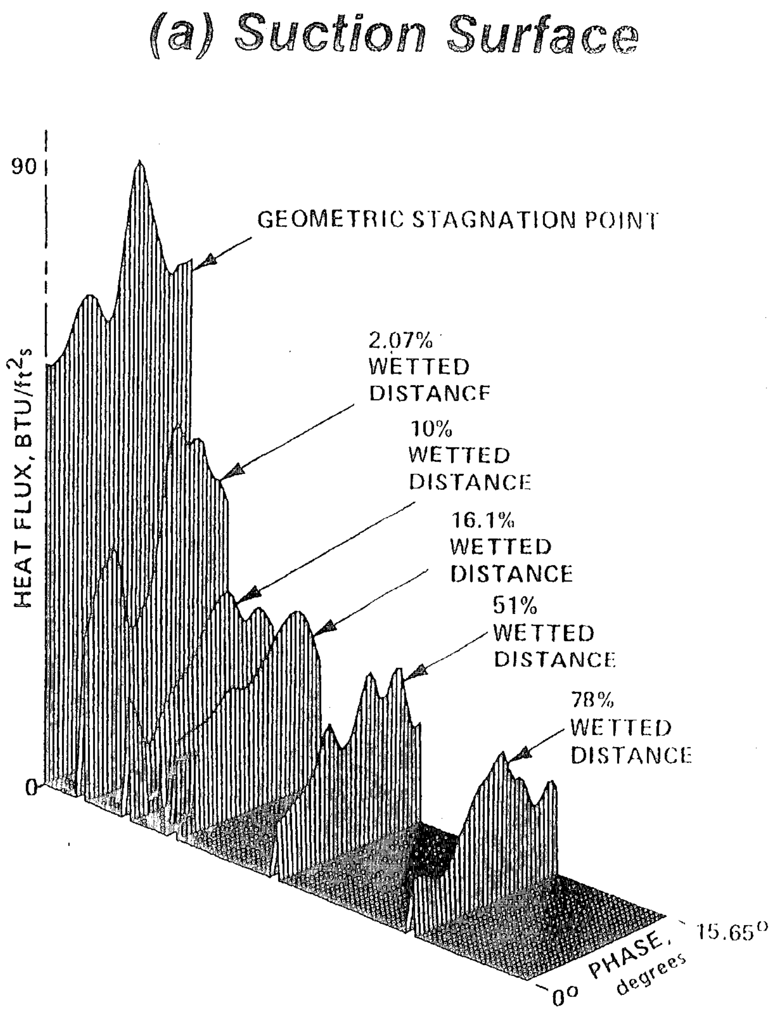
Heat Transfer and Measurements

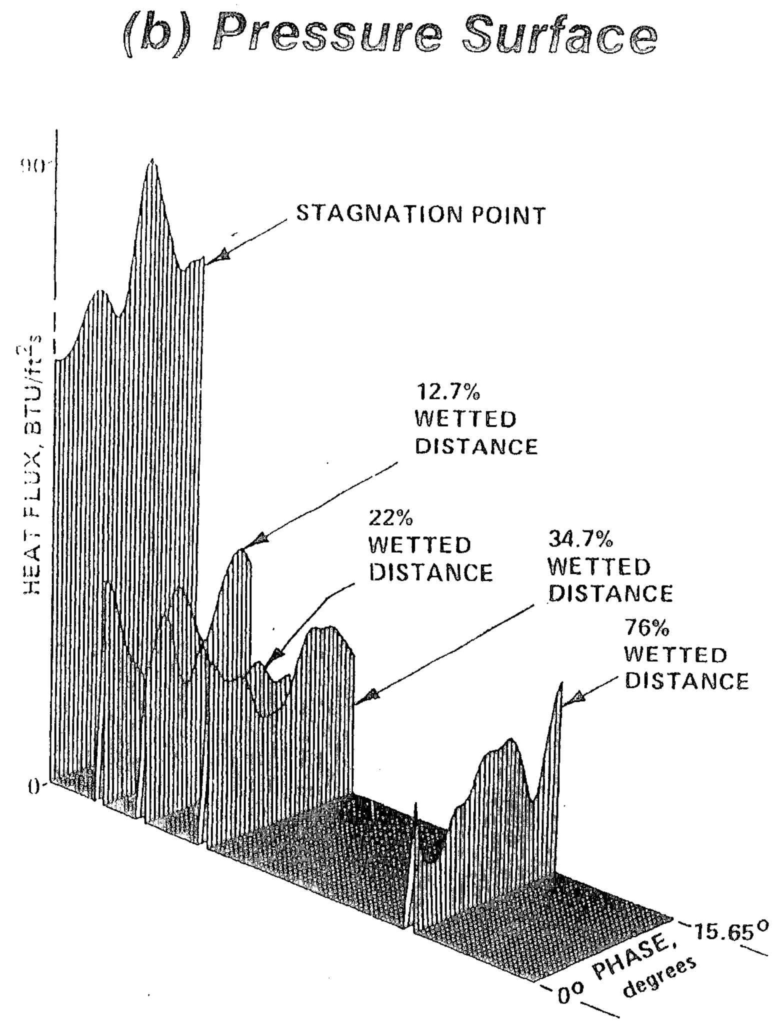
ASSESSMENT OF INSTANTANEOUS VS. AVERAGE EFFECTS

- Wakes/Shocks/Hot Streaks/Pressure Fluctuations
  - Transition
  - Stagnation Region
  - Film Cooling
  - ...
- Multi-Disciplinary (Thermal/Structural) Assessment
- Development of a Rigorous Framework for Modeling

UNSTEADY HEAT TRANSFER ON A TURBINE ROTOR

(Dunn, Seymour, Woodward, George, and Chupp - 1989)





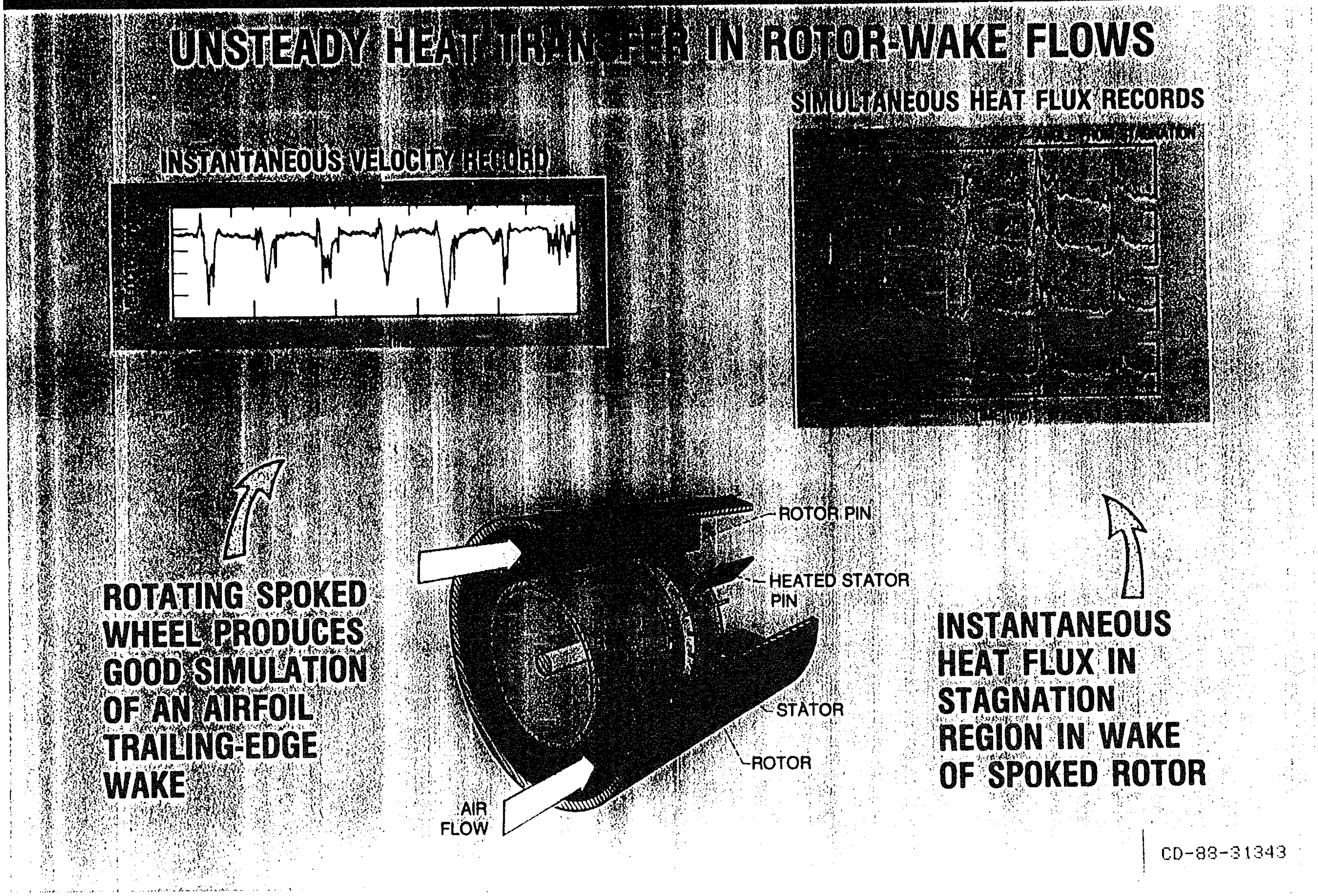
NASA CD-92-62347 Lewis Research Center

NASA
C-88-00820

National Aeronautics and
Space Administration
Lewis Research Center

INTERNAL FLUID MECHANICS DIVISION

NASA

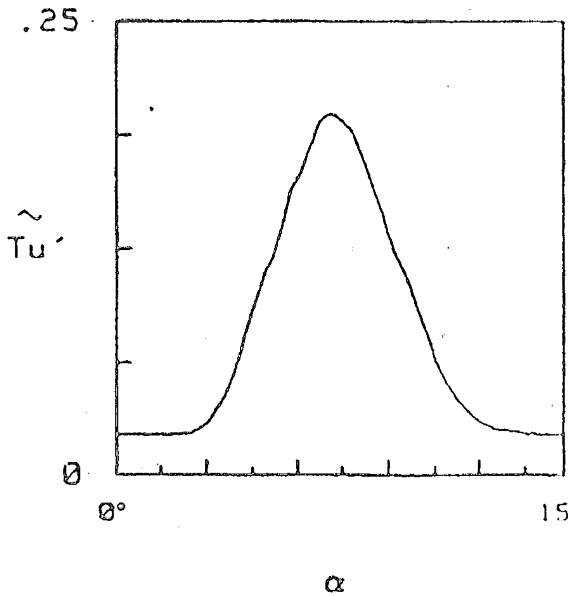


CD-88-31343

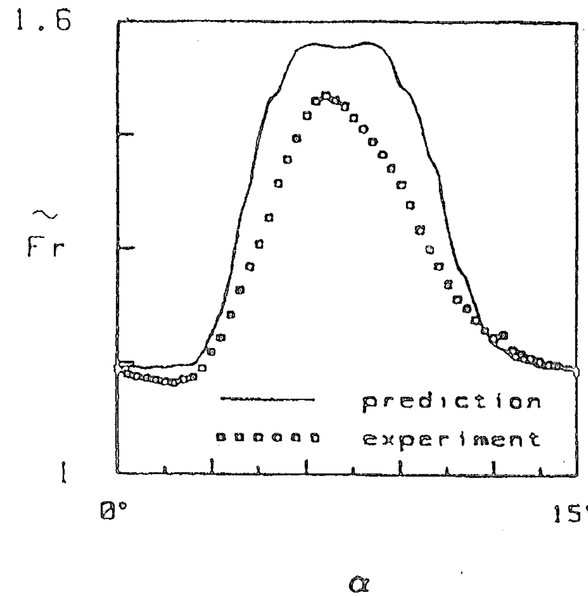
ENSEMBLE AVERAGE EFFECT OF WAKE ON HEAT TRANSFER

(O'Brien - 1990)

(a) Unsteadiness



(b) Heat Transfer



WINCAT
October 4, 1993

Some thoughts on the problems involved in measuring and describing heat transfer in unsteady flows

by

R. J. Moffat
Department of Mechanical Engineering
Stanford University
(415) 723-4501 VOICE
(415) 723-4548 FAX
NJ.RJM@FORSYTHE.STANFORD.EDU

What questions should we be asking

__Whose__ question are we trying to answer, and __what kind__ of answer do they need?

__Diff'rent folks need diff'rent strokes!__

Thermal Designers need to know -

How is the average "h" affected

Boundary Layer Modelers need to know-

How to describe the effect,
using the present code.

Turbulence Modelers need to know-

How do I change my turbulence model to
account for this effect.

THREE LEVELS OF QUESTIONS

LEVEL 1 -- WHAT HAPPENS?
ex.: HOW IS h AFFECTED BY UNSTEADINESS

LEVEL 2 -- BY WHAT MEANS?
ex.: WHAT DO THE MEAN VELOCITY AND TEMPERATURE PROFILES LOOK LIKE?

LEVEL 3 -- WHAT ARE THE UNDERLYING PHYSICS?
ex.: HOW HAS THE UNSTEADINESS ALTERED THE TURBULENT TRANSPORT

PAYOFF STRATEGIES

STAY AT LEVEL 1 -
UNTIL YOU KNOW WHERE THE ACTION IS.

GO TO LEVEL 2 -
TEST YOUR PRESENT MODELS AGAINST THE DATA, THEY MAY BE GOOD ENOUGH!

DON'T MIX LEVELS IN ONE EXPERIMENT

WHAT SEQUENCE OF EXPERIMENTS WOULD I RUN?

- <u>SCREENING EXPERIMENTS (LEVEL 1)</u>
  OBJECTIVE:
  TO IDENTIFY SITUATIONS LEADING TO AGRESSIVE HEAT TRANSFER

  OUTPUT:
  LOCAL HEAT TRANSFER, TIME-AVERAGED, BUT SPATIALLY RESOLVED
  MEAN PROFILES AND SIMPLE STATISTICS
  CHARACTERIXATION OF UNSTEADINESS

- <u>DIAGNOSTIC EXPERIMENTS (LEVEL 2)</u>
  OBJECTIVE:
  TO RELATE THE INCREASE IN HEAT TRANSFER TO THE FLUID MECHANICS EVENTS.

  OUTPUT:
  DETAILS OF THE TURBULENT TRANSPORT, SUFFICIENT TO REVEAL THE MECHANISM OF AUGMENTATION.

- <u>CFD EXPERIMENTS</u>
  OBJECTIVE: DEVELOP A MODEL OF THE INTERACTIONS

- <u>CHALLENGE THE MODEL PREDICTIONS IN THE LAB</u>

  - <u>CHALLENGE THE MODEL PREDICITONS IN THE ENGINE</u>

What kinds of unsteadiness should we study?

The less we know about the physics, the closer we should stick to reality.

Let the engine vote!

- **What drives the unsteadiness in an engine?**
- **Which parameters are unsteady: V, T, P?**
- **Are the variations correlated?**
- **Are the disturbances local or global?**
- **Are they 1-D, 2-D, or 3-D?**
  What does a 1-D disturbance look like?
  A 2-D disturbance?
  A 3-D ?
- **Are they random, periodic, or quasi-periodic?**

  e.g., $U(t) = \overline{U} + \langle U \rangle + u'$

Situations that produce unsteady flows

Compressor intake disturbances

Compressor instability

Combustion chamber instability

Wakes from struts and structures

Blade-wakes passing

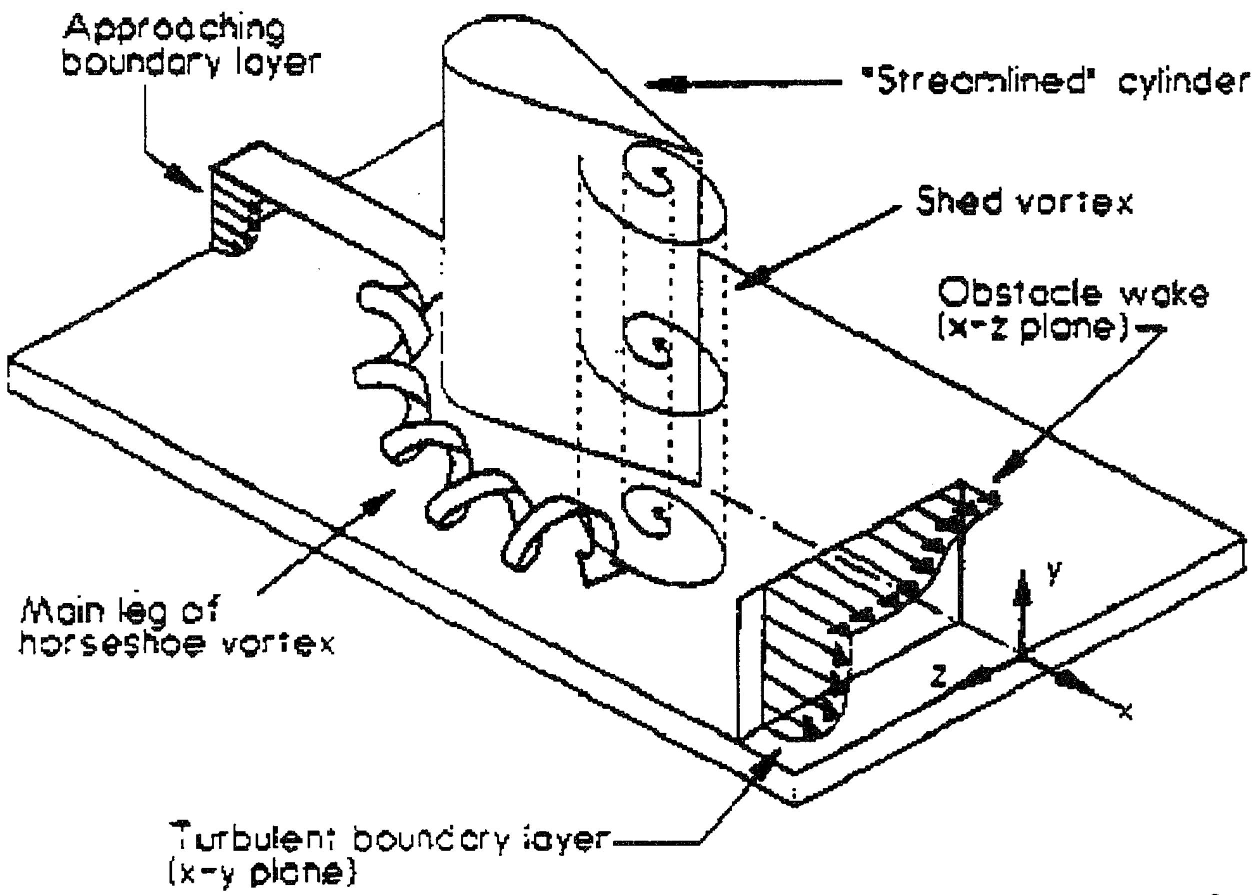
Separations and reattachments

Impingement of jets

What kinds of unsteadiness do these produce?

In the near field, local, 2-D or 3-D disturbances.

In the far field, global 2D or 1-D unsteadiness



WROBLEWSKI, 1993 NHTC

WHAT TYPES OF MEASUREMENTS DO WE NEED?

THAT DEPENDS ON WHAT LEVEL OF QUESTION YOU ARE TRYING TO ANSWER

<u>FOR LEVEL 1 WE NEED:</u>

SPATIALLY RESOLVED,
TIME-AVERAGED
HEAT FLUX AND SURFACE TEMPERATURE

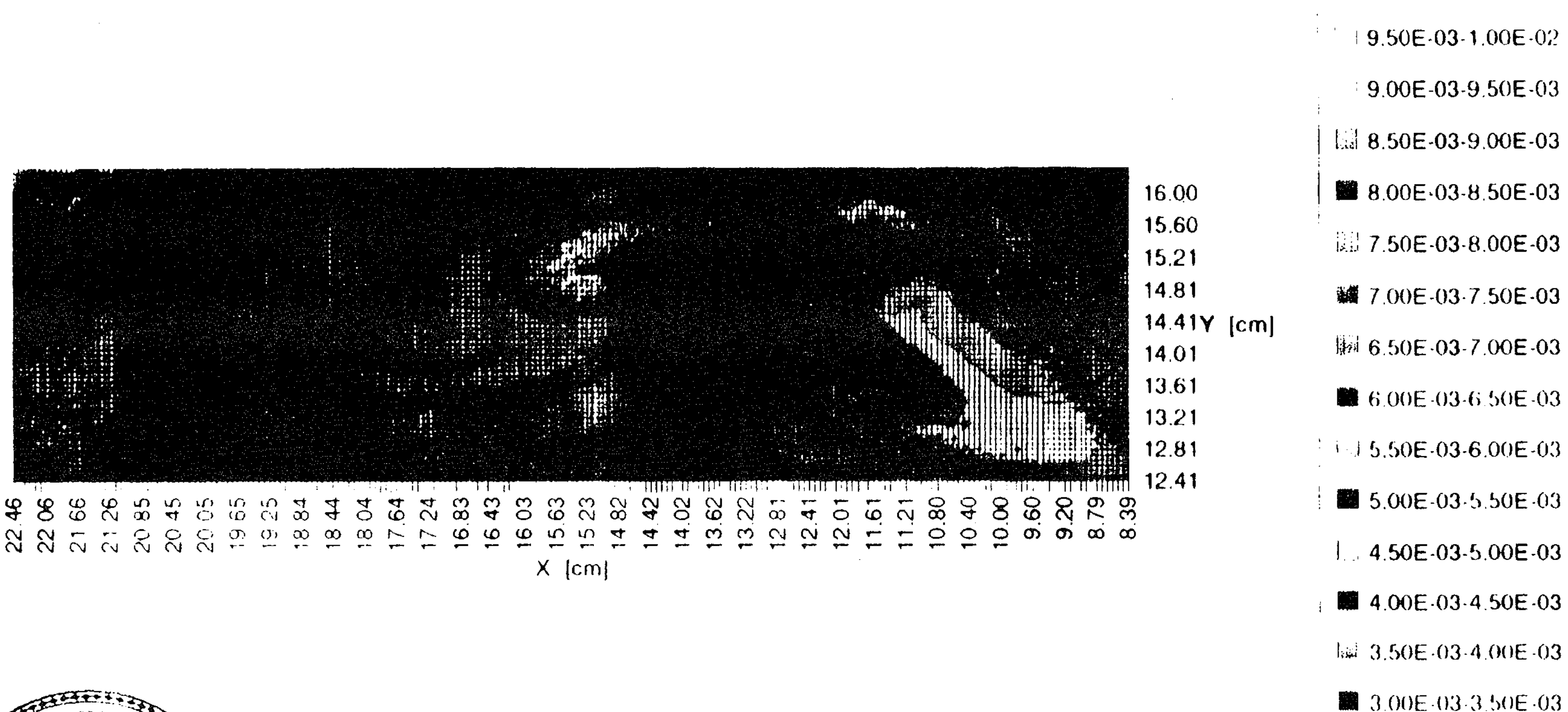
<u>FOR LEVELS 2 AND 3 WE NEED:</u>

TIME-RESOLVED MEASURMENTS,
AT CRITICAL LOCATIONS, OF
FLUID VELOCITY, TEMPERATURE, AND PRESSURE
SURFACE TEMPERATURE AND HEAT FLUX

BOTH TYPES OF MEASURMENTS CAN BE HAD NOW,
WITH SOME EFFORT.

Sudeep Kumar
Marcus Murbach
Pavan Vaish
Ron Worth

Contour for St - h=1.5cm, alpha=45deg

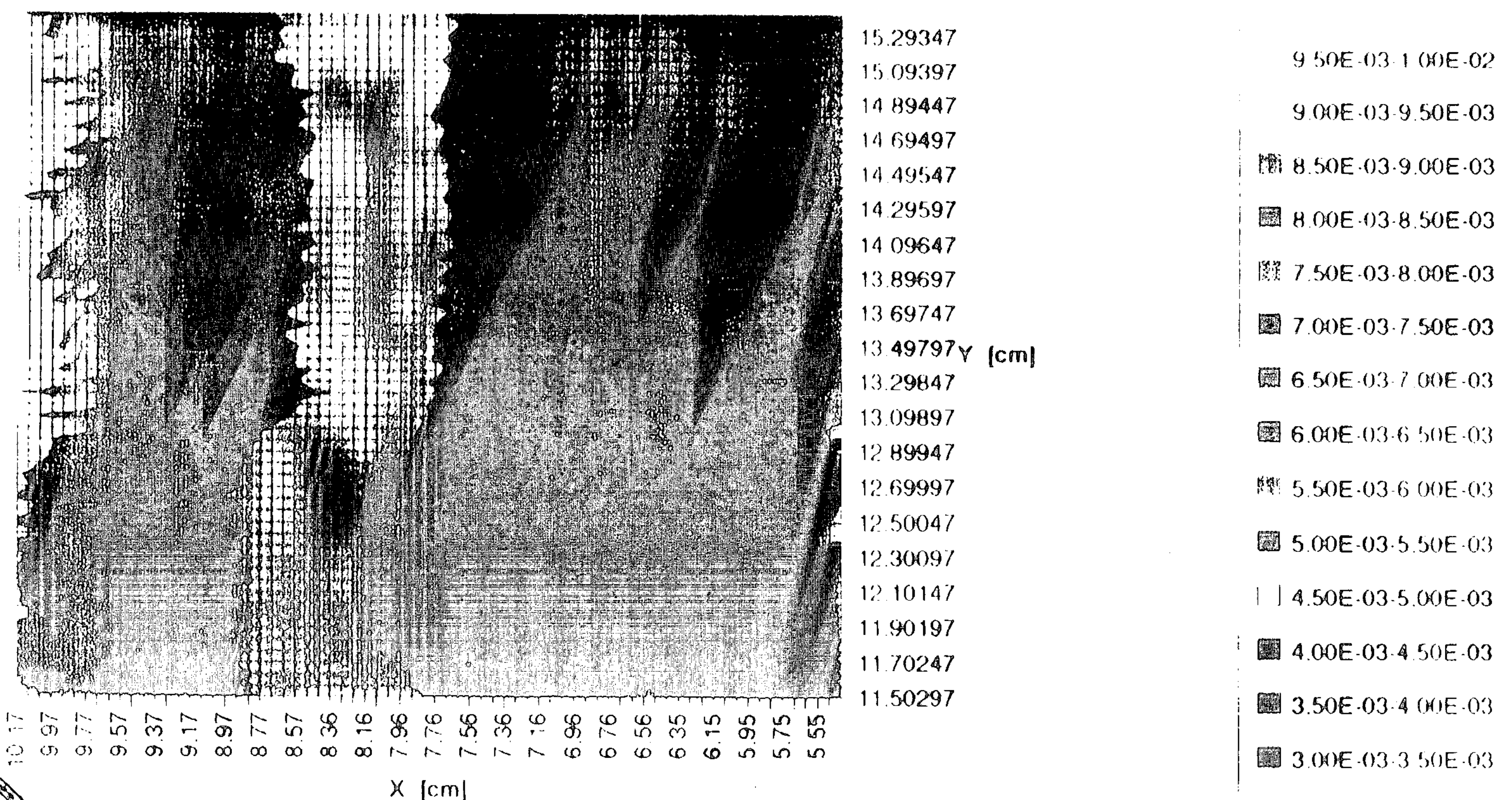


Thermosciences Division, Stanford University

8

Sudeep Kumar
Marcus Murbach
Pavan Vaish
Ron Worth

Baseline



Thermosciences Division, Stanford University

8B

COMPARING UNSTEADY DATA WITH STEADY DATA:

A NECESSARY, BUT TROUBLESOME, STEP

- COMPARISIONS ARE LIKE PARTIAL DERIVATIVES -- IF THEY ARE TO BE USEFUL, YOU MUST DESCRIBE WHAT IS BEING HELD CONSTANT
- THE APPROPRIATE BASELINE DEPENDS ON THE END USE OF YOUR DATA

<u>EXAMPLE:</u>
SUPPOSE YOU WISH TO USE THE 2-D TURBULENT BL ON A FLAT PLATE AS YOUR BASELINE, SHOULD YOU MAKE YOUR COMPARISON AT:

- SAME X-LOCATION, SAME TIME-AVERAGED MEAN VELOCITY?

OR

- SAME ENTHALPY THICKNESS REYNOLDS NUMBER?

THESE ARE APPROPRIATE FOR DIFFERENT END-USDES OF THE DATA.

- HOW MUCH IS h AFFECTED AT THIS LOCATION?
- HAVE THE FUNDAMENTAL TRANSPORT PROCESSES CHANGED, OR JUST THE BL THICKNESS?

What can we expect ?

The present heat transfer literature shows about +/- 20% scatter (on a good day) even for simple, steady-flow situations.

What can we reasonably expect to see in unsteady flows?

Probably worse but not because the measurements will be less accurate --

The increased scatter among different sets of results will probably arise from <u>situational variance</u>: rigs which are described as being similar producing different flow fields.

We need some careful thinking here, to define unsteady flows which are relevant to engine problems, yet simple to produce, and repeatable.

Ideally, we should first find out what are the significant features of the unsteadinesses that we care about, in engines, so we can emphasize those features, but we probably won't. We just have to do the best we can.

Defining h

The heat transfer coefficient is a defined quantity - not a physical one. Its value depends on 3 quantities:

$$h = \frac{q''_{conv}}{(T_o - T_{Ref})}$$

By definition, h is related to the shape of the temperature distribution in the BL, and to the reference temperature.

$$h = \frac{-k \partial T / \partial y}{(T_o - T_{Ref})} = -k \frac{\partial T^*}{\partial y}$$

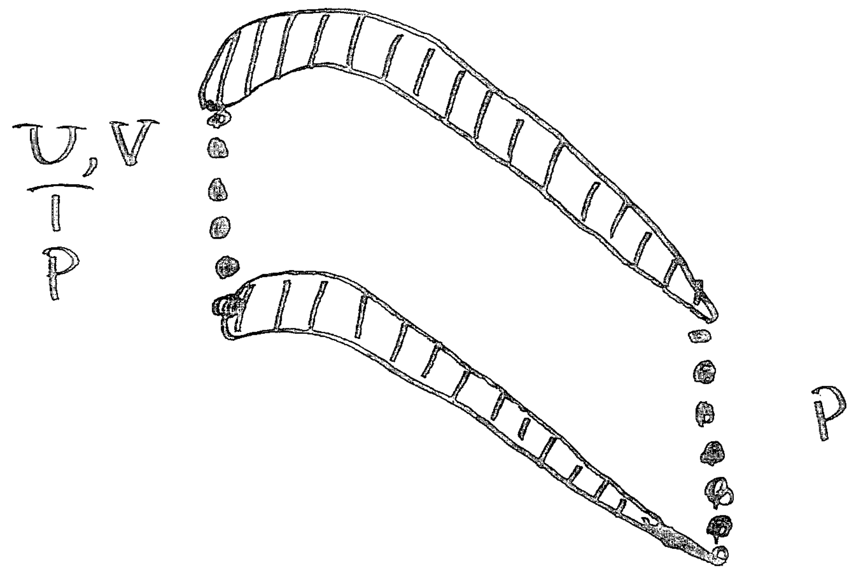
or

$$Nu = \frac{hL}{k} = -\frac{\partial T^*}{\partial y^*}$$

In unsteady situations, we should measure q" and (T_O - T_{Ref}) at the same instant, or over the same time interval. Temperature distributions in unsteady boundary layers can be pathological.

11

UNSTEADINESS AND TURBULENCE



$$U = U + \tilde{U} + u'$$

$$T = T + \tilde{T} + t'$$

$$P = P + \underbrace{\tilde{P} + p'}_{}$$

U, T, and P are functions of position as well as of time

THE DISTINCTION BETWEEN "PERIODIC" AND "RANDOM" IS IN THE EYE OF THE BEHOLDER, AND PROBABALY DEPENDS ON BOTH SCALE AND FREQUENCY.

QUESTION: HOW MUCH DETAIL MUST WE PROVIDE TO ASSURE PREDICTABLE BEHAVIOR?

A SUGGESTION CONCERNING STEADY / QUASI-STEADY / UNSTEADY

$$U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} - \frac{\partial}{\partial y}\left(\alpha_{TOT}\frac{\partial T}{\partial y}\right) = 0$$

IF ONLY U AND V ARE AFFECTED, SYSTEM IS QUASI-STEADY

IF THE TURBULENT TRANSPORT IS AFFECTED THE SYSTEM IS UNSTEADY

QUESTIONS:

1. WHAT IS THE APPROPRIATE STEADY SITATUION FOR COMPARISON?

2. CAN WE MEASURE THE HEAT TRANSFER ACCURATELY ENOUGH TO IDENTIFY A CHANGE?

EFFECTS OF VANE-BLADE INTERACTION ON TURBINE AIRFOIL HEAT TRANSFER

R. A. DELANEY

PRESENTED AT
WORKSHOP
ON
INHERENT NONSTEADINESS
IN
COMPRESSORS AND TURBINES
PURDUE UNIVERSITY
OCTOBER 4-6, 1993

Allison

GM

ALLISON/CALSPAN VANE-BLADE INTERACTION PROGRAM

- Objective: Acquire airfoil surface pressure and heat transfer code validation data for a transonic turbine stage
- Approach:
  - Perform test of full-scale transonic turbine stage
  - Investigate effects of variations in vane-blade spacing and setting angle
- Facility: 18.5" shock tunnel at Calspan Advanced Technology Center
- Airfoil Instrumentation:
  - High-response Kulite pressure transducers
  - Thin-Film heat flux gages

ALLISON/CALSPAN VBI PROGRAM

TURBINE GEOMETRY

Parameter	Stator	Rotor
Number of Airfoils	30	45
Chord (in.)	2.66	1.87
Chord/Spacing	1.32	1.39
Aspect Ratio	0.72	1.10
Hub/Tip Radius Ratio	0.82	0.81
Tip Radius (in.)	10.64	10.64

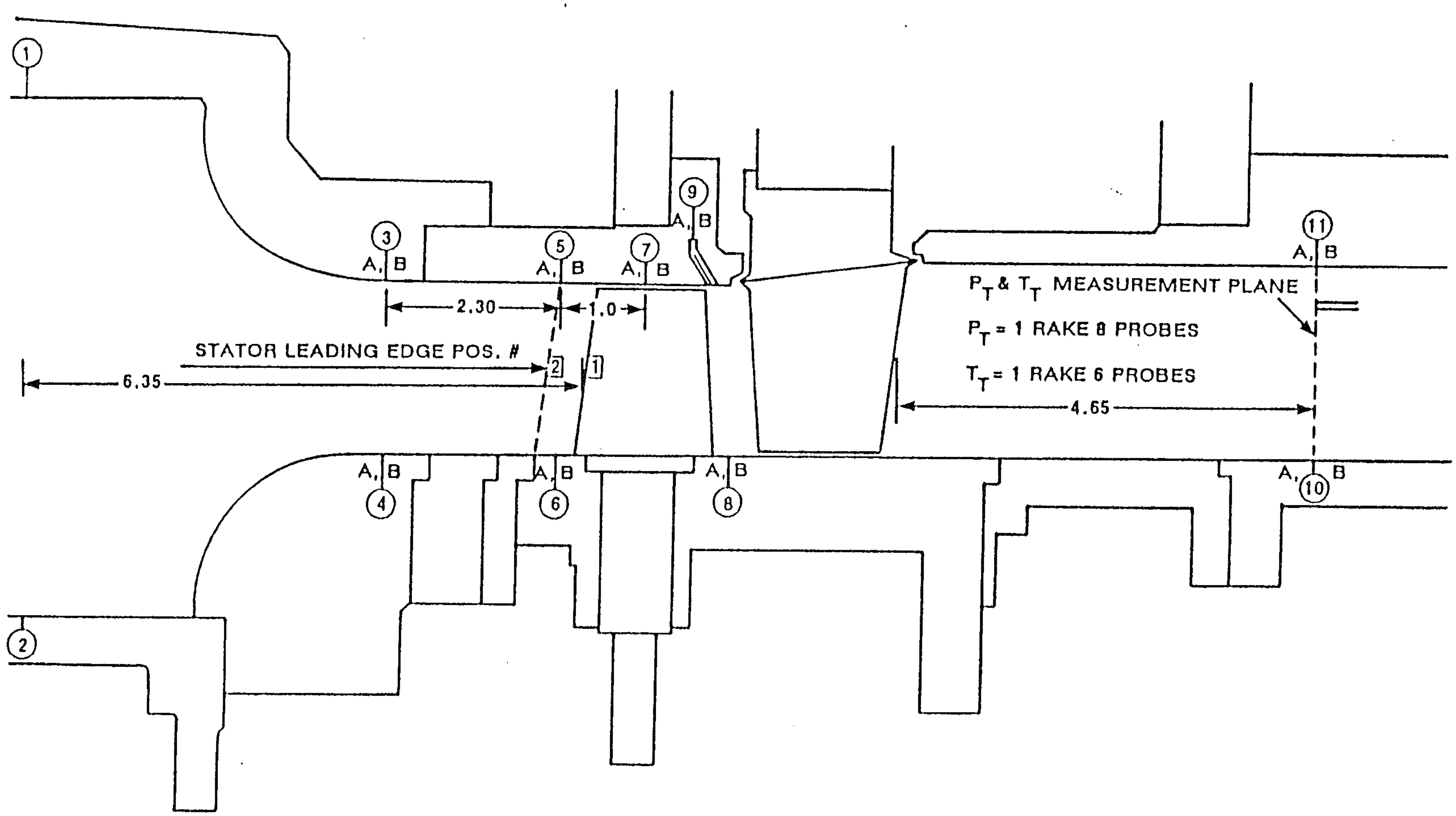
ALLISON/CALSPAN VBI PROGRAM

TURBINE AERODYNAMICS

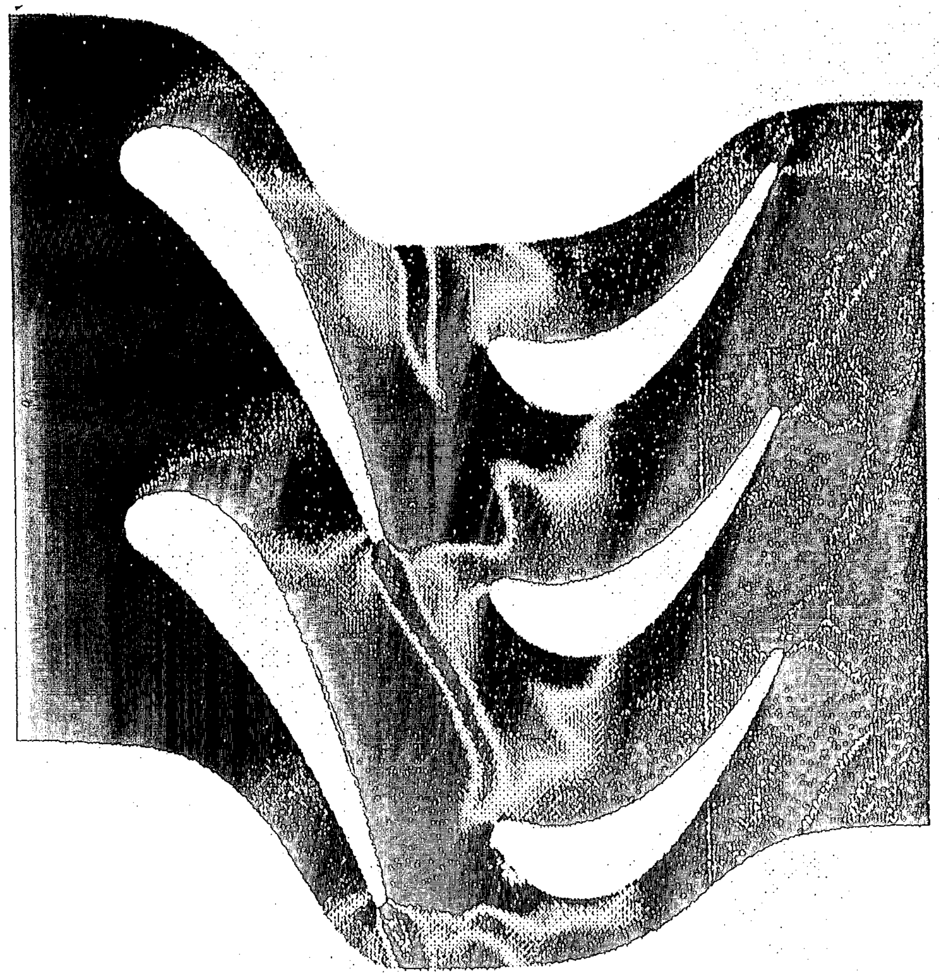
	Closed Vane Setting		Open Vane Setting	
Parameter	Stator	Rotor	Stator	Rotor
Rotor Speed (RPM)	----	11,400	----	11,000
Stage Expansion Ratio (Total-to-Static)	----	4.06	----	2.43
Inlet Relative Mach Number	0.164	0.483	0.197	0.406
Exit Relative Mach Number	1.121	1.054	0.918	0.880
Corrected Flow (lb/sec.)	22.57	----	27.7	----
Reduced Frequency	7.8	8.5	8.0	8.5
Vane Setting Angle (Deg.)	-61.0	----	-57.0	----
Vane-Blade Spacing (in. (% Cx))	.6 (40) 1.0 (66)		1.0 (64)	

ALLISON/CALSPAN VBI PROGRAM

RIG CROSS SECTION



VANE-BLADE INTERACTION

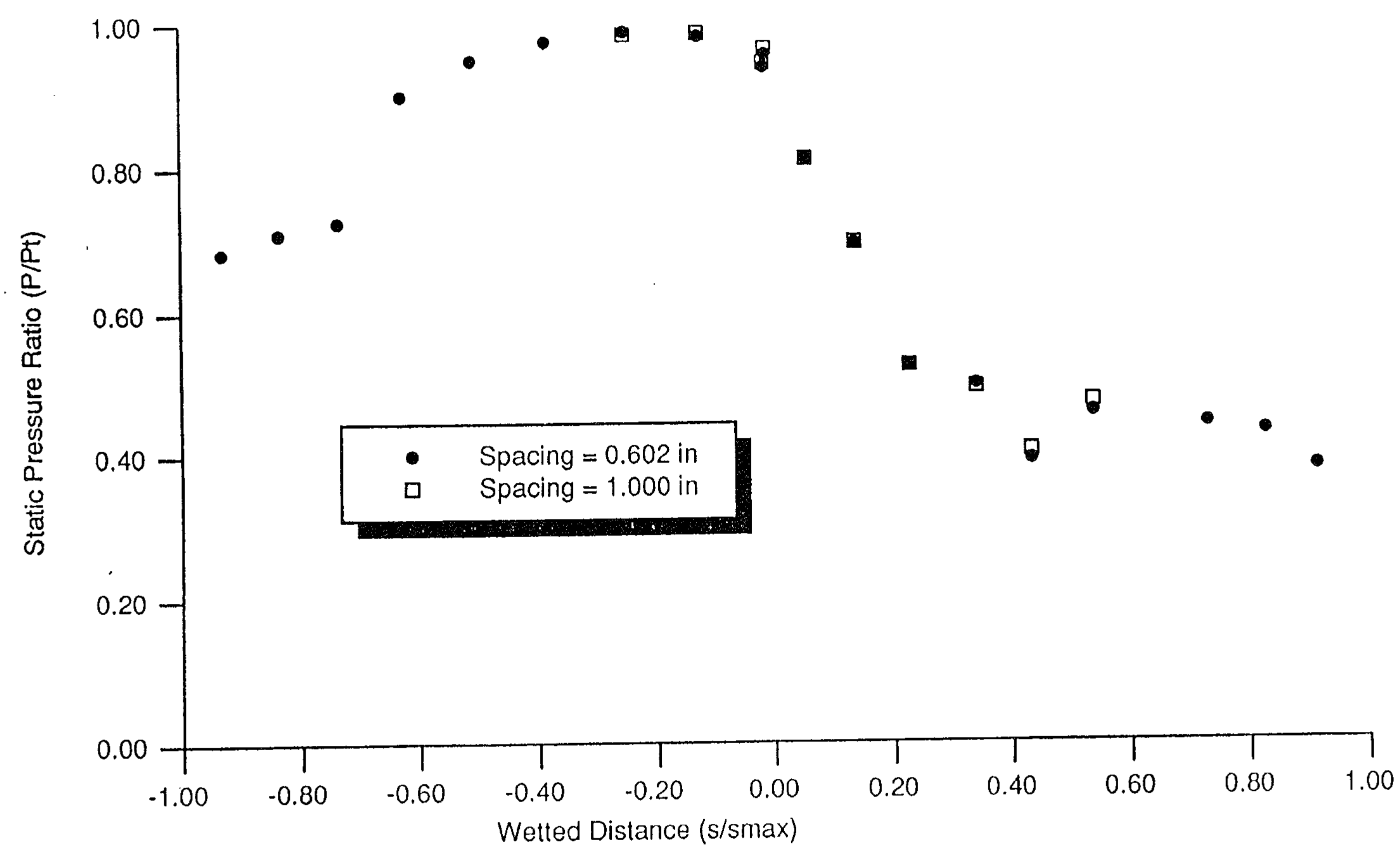


MACH CONTOURS

ALLISON/CALSPAN VBI PROGRAM

VANE TIME-MEAN PRESSURE DATA

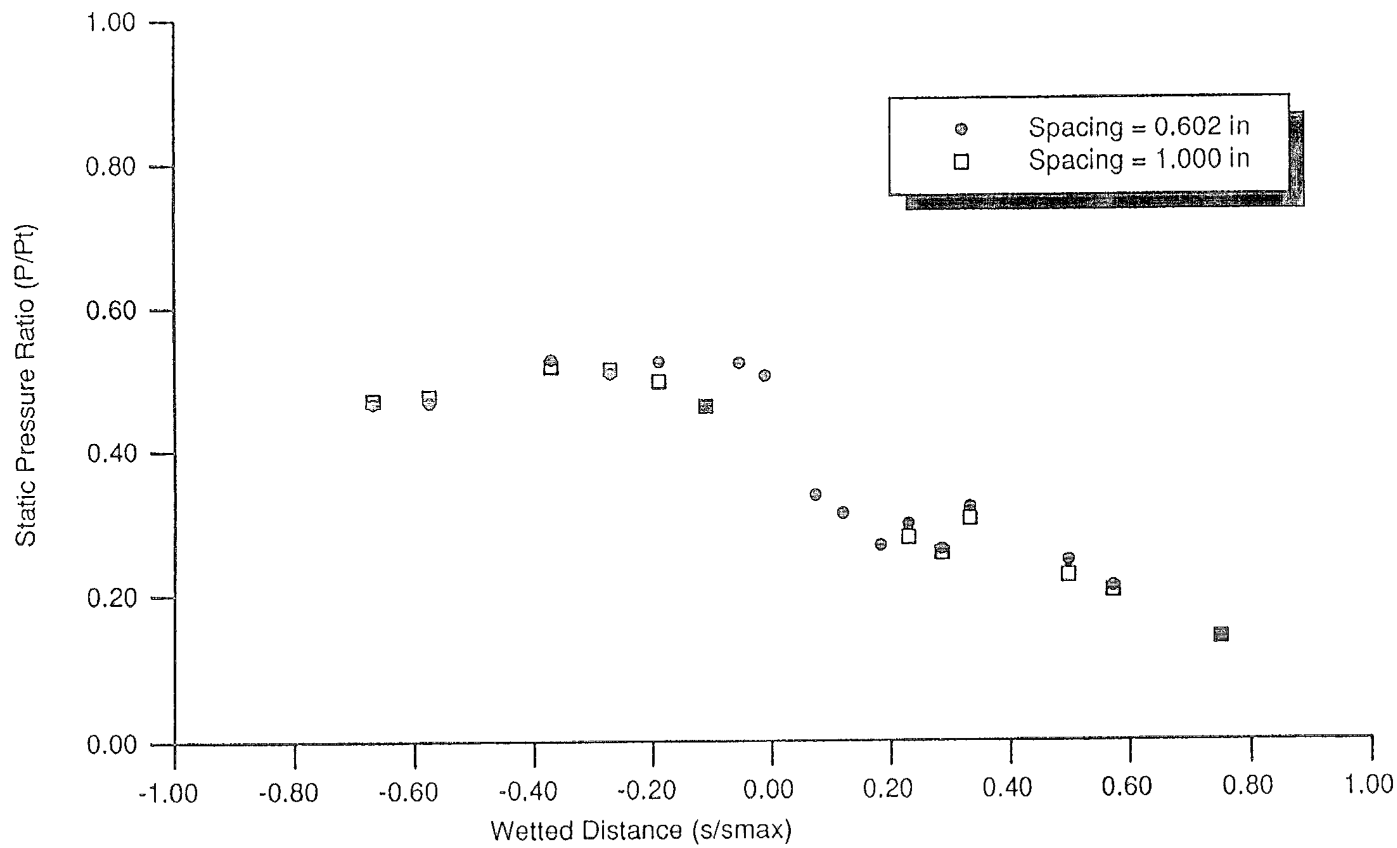
CLOSED VANE SETTING



ALLISON/CALSPAN VBI PROGRAM

BLADE TIME-MEAN PRESSURE DATA

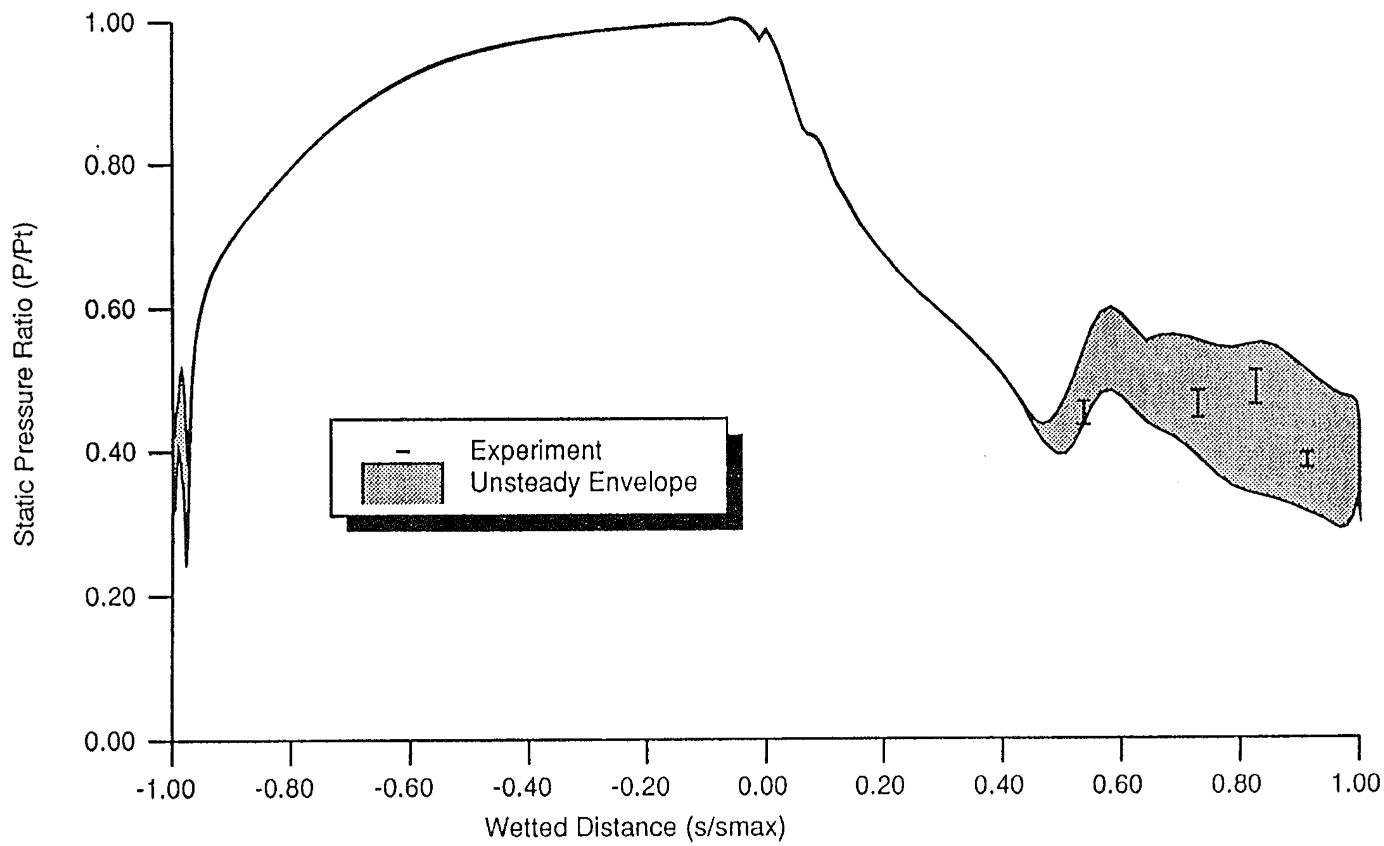
CLOSED VANE SETTING



ALLISON/CALSPAN VBI PROGRAM

VANE UNSTEADY PRESSURE ENVELOPE

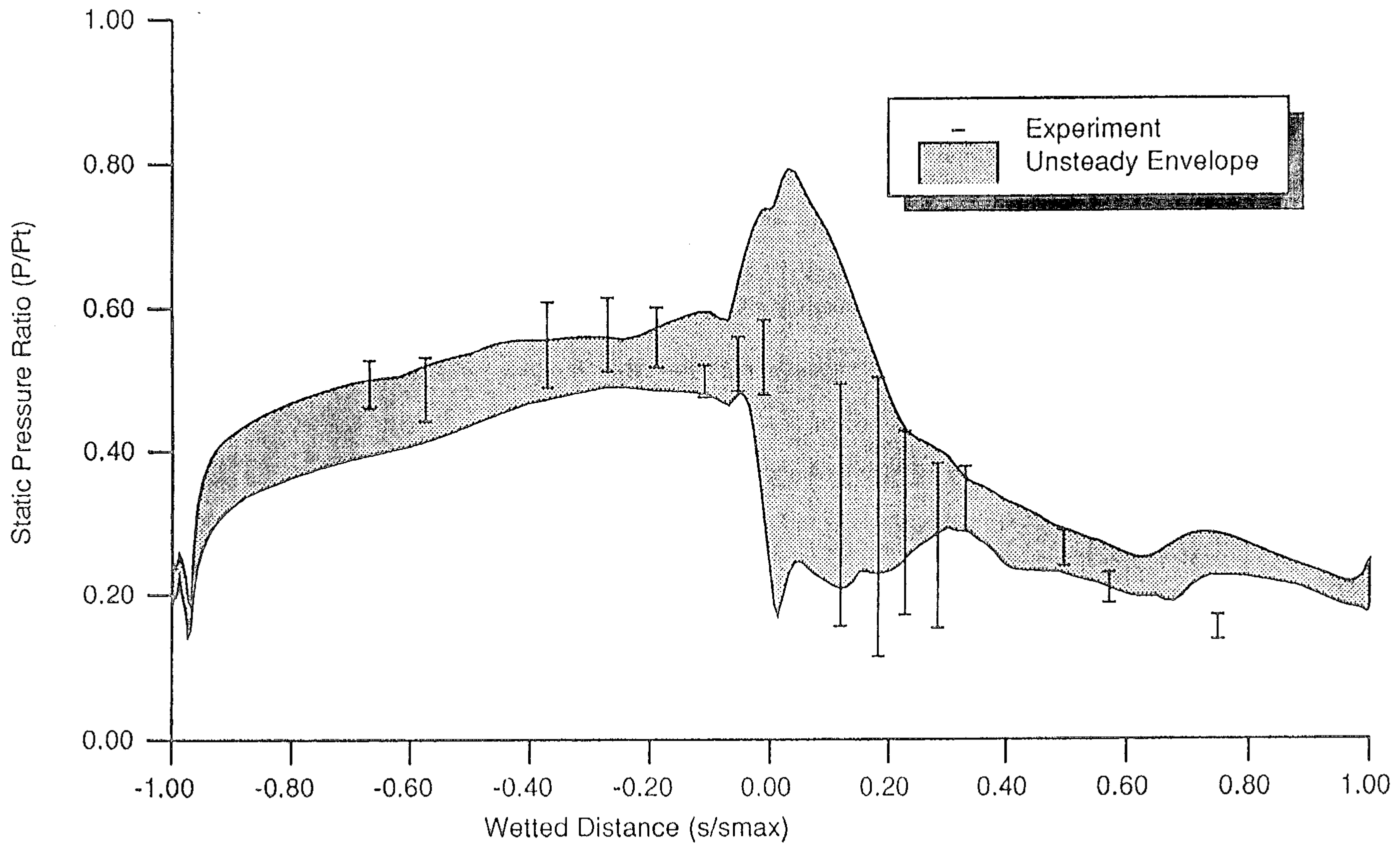
CLOSED VANE SETTING, SPACING=0.6 IN



ALLISON/CALSPAN VBI PROGRAM

BLADE UNSTEADY PRESSURE ENVELOPE

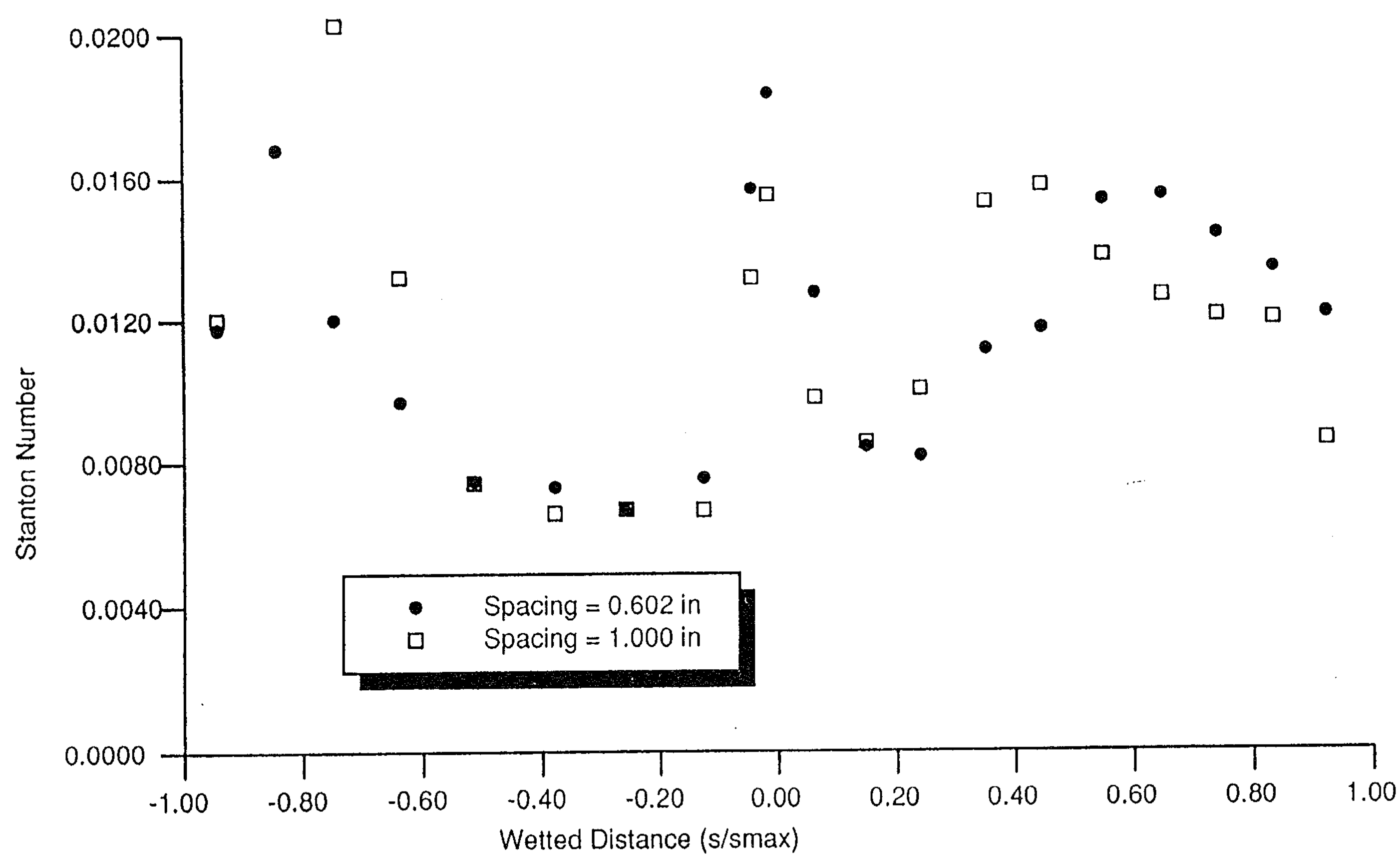
CLOSED VANE SETTING, SPACING=0.6 IN



ALLISON/CALSPAN VBI PROGRAM

VANE TIME-MEAN HEAT TRANSFER

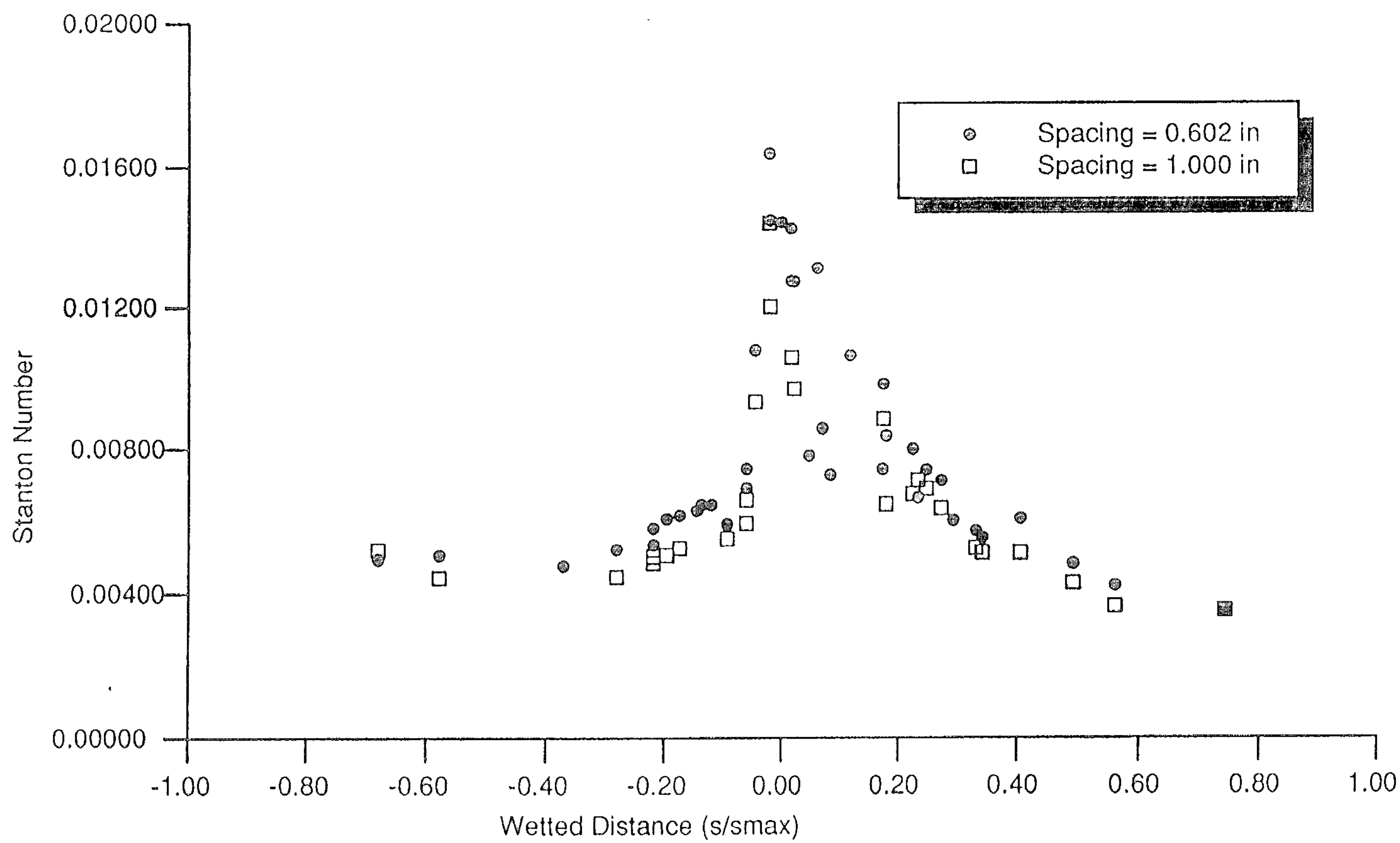
CLOSED VANE SETTING



ALLISON/CALSPAN VBI PROGRAM

BLADE TIME-MEAN HEAT TRANSFER

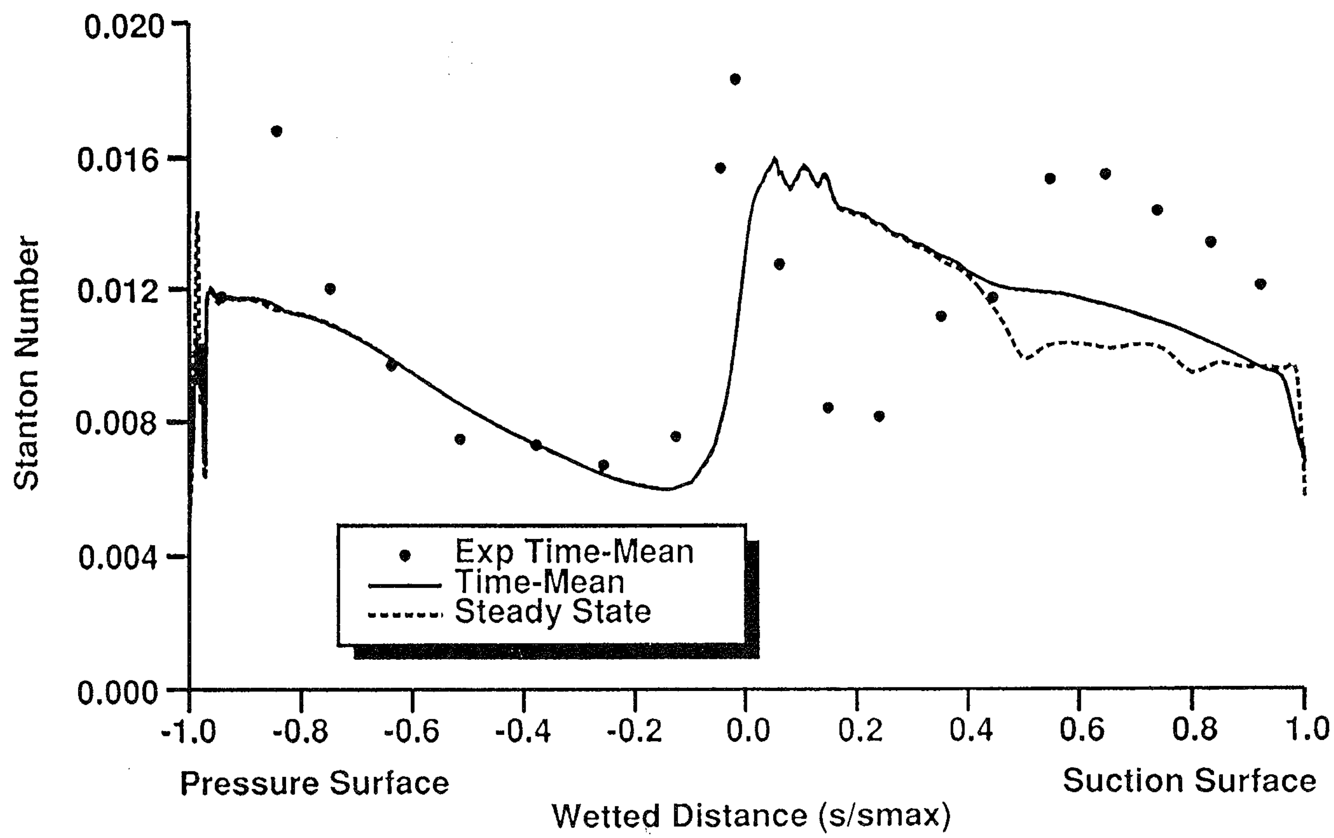
CLOSED VANE SETTING



ALLISON/CALSPAN VBI PROGRAM

VANE TIME-MEAN HEAT TRANSFER

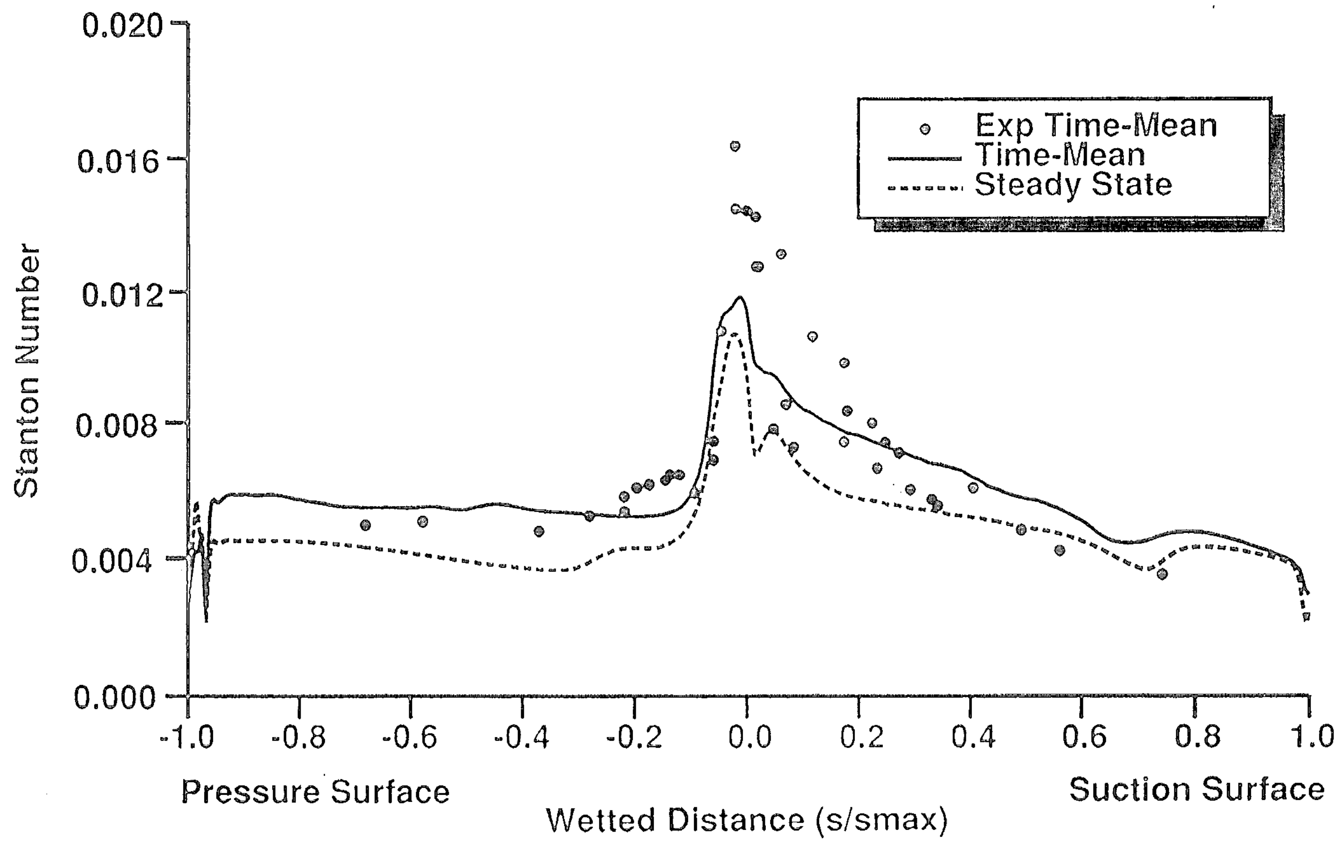
CLOSED VANE SETTING, SPACING=0.6 IN



ALLISON/CALSPAN VBI PROGRAM

BLADE TIME-MEAN HEAT TRANSFER

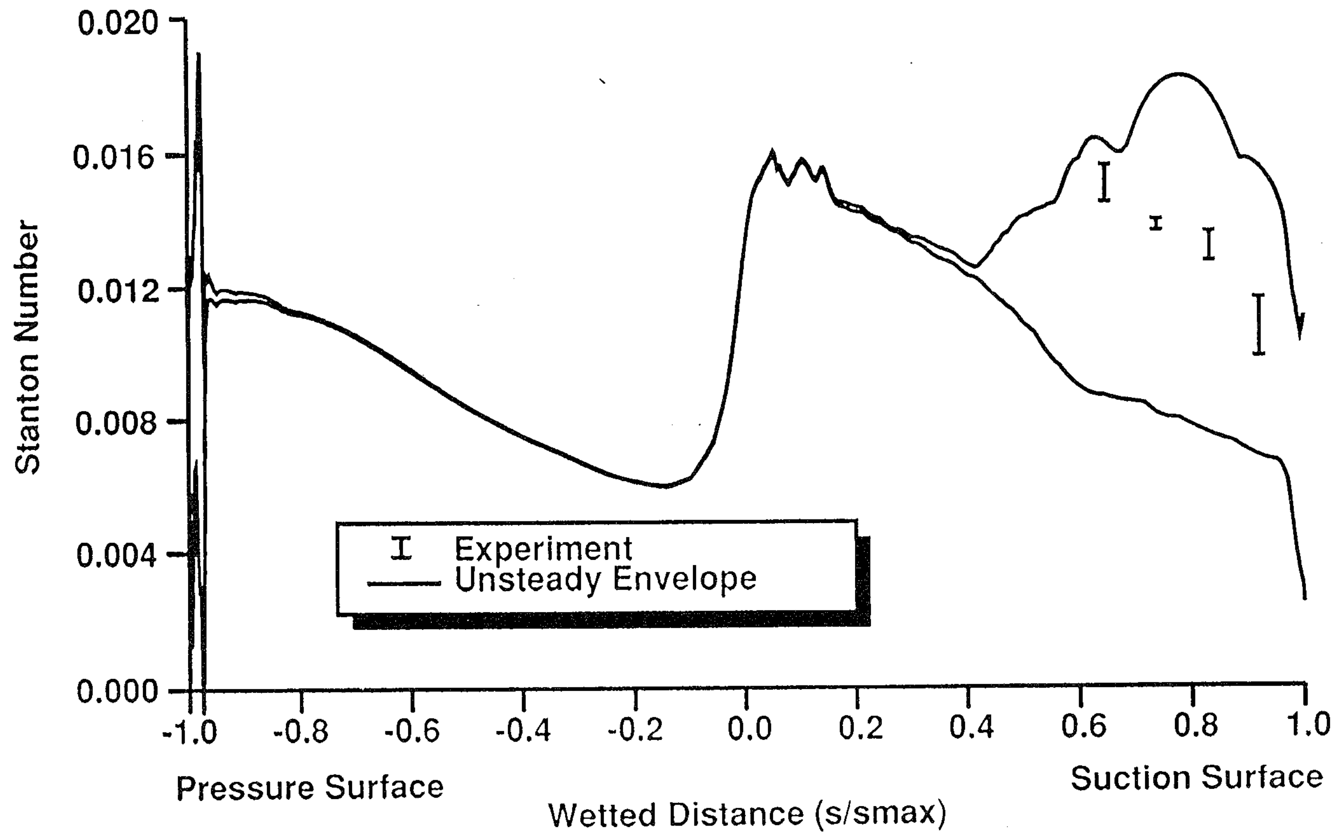
CLOSED VANE SETTING, SPACING=0.6 IN



ALLISON/CALSPAN VBI PROGRAM

VANE UNSTEADY HEAT TRANSFER ENVELOPE

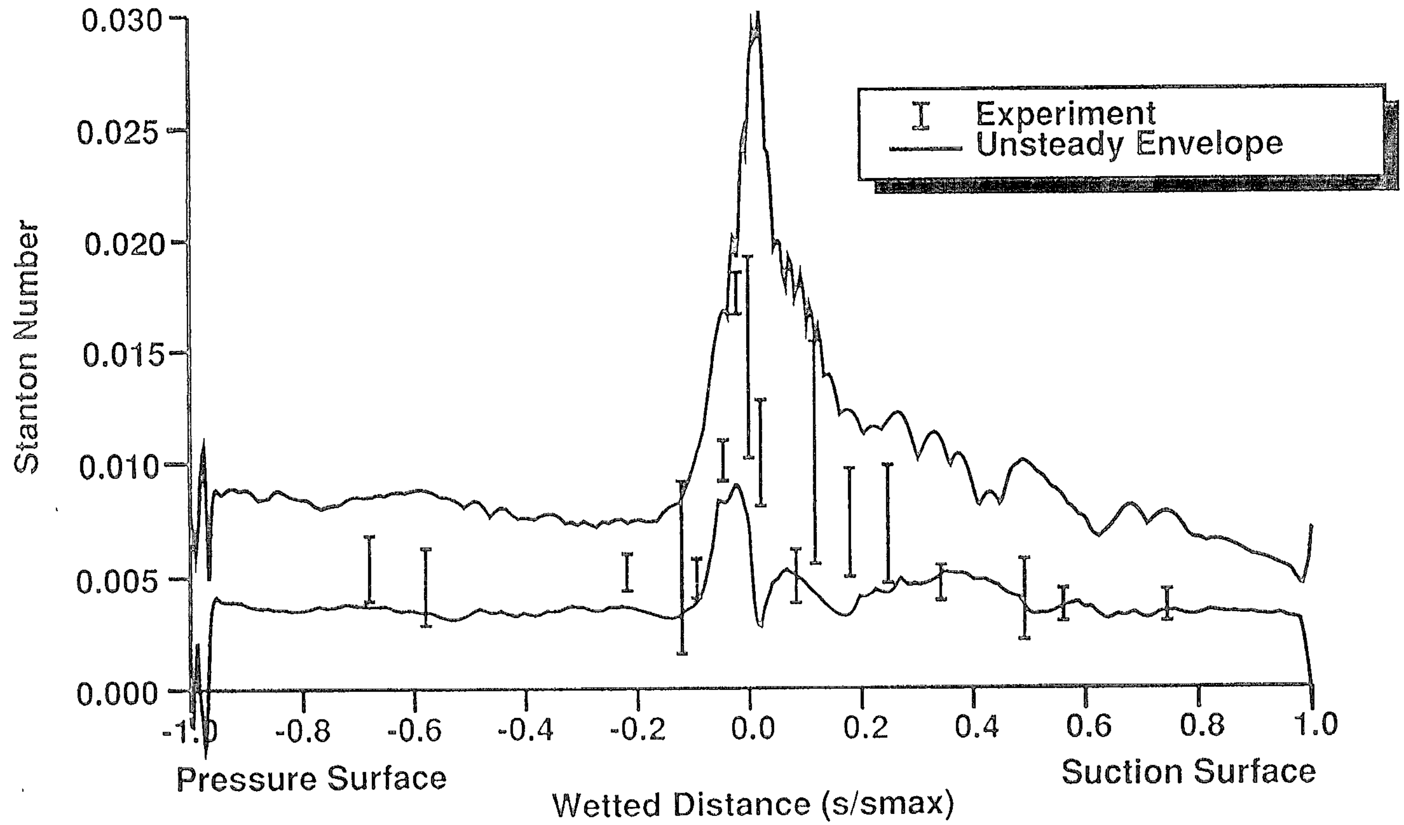
CLOSED VANE SETTING, SPACING=0.6 IN



ALLISON /CALSPAN VBI PROGRAM

BLADE UNSTEADY HEAT TRANSFER ENVELOPE

CLOSED VANE SETTING, SPACING=0.6 IN



ALLISON/CALSPAN VBI PROGRAM

EFFECTS OF INTERACTION

- Vane
  - Significant unsteadiness on vane suction surface downstream of throat
  - Boundary layer transition location may be affected by interaction
- Blade
  - Large amplitude unsteadiness near leading edge due to vane trailing-edge shock
  - small/moderate effect on time-mean aerodynamics
  - Significant effect on leading-edge heat transfer

• GROUP DISCUSSIONS

GROUP A
COMPRESSORS-SUMMARY OF THE DISCUSSION SESSION

The session was well attended, with most of the compressor specialists at the meeting present. The session was hampered by the fact that eight of those present had presentations to give the following day. They clearly did not want to give their presentations at the discussion session.

The chair had prepared a series of questions to challenge the audience, but decided first to solicit suggestions for important unsteady flow issues that could impact design.

There was a general concurrence that the most fundamental source of unsteadiness, that due to "blade count", was absent from compressor design systems. Sehra asked, "How do we use unsteady effects to improve efficiency. Waterman said that there was currently no rational aerodynamic reason for selecting blade & vane count. Deviation, losses and blockage are the "unknowns" in the steady-flow design systems. Their dependencies on blade count (rather than solidity and Reynolds number) are not known. Adamczyk asked whether the inclusion of unsteady effects would most impact on-design or off-design performance. He reported that NASA had held a workshop (a small invited group) on unsteady effects less than a year ago. They had concluded that, for the near term, transition was an important issue, but not turbulence modelling ("the last thing we want is another turbulence model"). They also concluded that whether blade count mattered significantly should be established experimentally. Some discussion followed concerning the need for, and importance of, "flow modelling rather than "turbulence modelling".

Tan said that it was necessary to understand the unsteady effects in order to know what the inclusion would buy (in on-design or off-design performance). Epstein stated that we certainly need to understand the unsteady behavior for control purposes.

The fundamental design issue of choosing blade count took up a significant fraction of the discussion. Wisler and Epstein argued whether high or low aspect ratio would be the future direction for compressors, and the competing effects of length, weight and durability were brought up. The discussion served to bring out the fact that, with the exception of Roy Smith's 1991 AIAA paper on propulsion wake effects, little could be said on the issue. Not only was this true for axial machines, the effect of blade numbers in centrifugal compressors was also uncertain. In centrifugal geometries, it is known that there are significant effects of

the inherent unsteadiness from the rotor on the performance of the diffuser, but there are no methods available to quantify and take advantage of such effects.

The opinion of several industry people was that their companies would only be interested in a program to understand unsteady effects if you would tell them how to reshape the blading to improve performance. For the coming years, all research activity not contributing to improving existing products has no support. (Wisler) for this reason, they would certainly welcome the participation of university students to work on these problems in their laboratories, if the government will fund them.

Statements were made by Fleeter and Verdon on the importance of predicting aeromechanical effects in the unsteady machine environment. There was no real opposition to these statements and the discussion was short.

Three dimensional, unsteady viscous effects are involved in case wall and tip-clearance effects. The sensitivity of compressors to tip-clearance changes and that this is a persistent and critical problem to industry, came out in the discussion. How to design to reduce the sensitivity is an issue of importance. The possibility of using the combination of CFD and experiment to derive effective case wall geometries to enhance stability was suggested.

Active control of compressor stability appeared to be of more importance to some companies than to others. The general consensus was however, that the government should carry out the necessary research and development. (Its application in military aircraft, rather than civilian is, by far, the more promising).

Finally, Moore raised the issue of noise, a guaranteed outcome of inherent unsteadiness. He suggested that the acoustic behavior be included in CFD analyses so that ways to reduce noise might be found. Again, no opposition was forthcoming.

After the chair listed the issues which had been raised and discussed, the session was adjourned.

COMPRESSORS - REVIEW AND SUMMARY RECOMMENDATIONS

The presentations of individual speakers, the discussion session and later interactions with specific participants, clearly identified the recurring research issues and most significant research opportunities. The same points were raised

repeatedly by different speakers in different ways. Kerrebrock of MIT and Coons of Pratt & Whitney both gave motivations for a focused research effort on inherent unsteadiness. Kerrebrock pointed to predictable gains in the areas of noise, performance (losses), structural integrity, design system projections, and in extending stability limits. (Unpredictable benefits might also accrue from simply developing fundamental understanding). Coons pointed to the considerable potential pay-off to industry from reduced time-to-market and reduced costs of development. There was agreement on the sources of unsteadiness that needed attention; namely, blade passing effects, local flow instabilities (separations), aeromechanical instabilities and system instabilities. Three different length scales characterize these effects; namely, boundary layer (or turbulence), blade or passage scale, and systems length scale.

The same scales were referred to by Baghdadi of Pratt & Whitney who addressed each one in turn. Currently they use two-equation algebraic turbulence modelling. He pointed to the need to include anisotropy due to curvature and to describe effects such as shock-boundary layer interaction. Blade row interactions are largely ignored presently, (although some development experiences have suggested a definite significance). System stability is projected currently using loading limits based on experience and one-dimensional dynamic models. There is a need for a system simulation based on 3-D unsteady flow descriptions which can incorporate inlet distortion.

Copenhaver of Wright Laboratory also identified the same three scales, pointed to the fact that unsteady effects are not in their design system, and asked what is important as stage loading is increased. He described an experiment which is underway at WPAFB to evaluate what magnitude of effect can be attributed to changes in blade number (or blade wakes). He emphasized the importance of "staying close to the design system" if research results are to be transitioned usefully.

Okiishi of Iowa State University, in his review, saw similar motivations and issues; namely, aeromechanical failure, recoverability, wake ingestion benefits and noise reduction. He also listed the coupling of CFD and measurements as the key to making progress in the proposed program.

Adamczyk of NASA Lewis Research Center reported on a recent workshop that he had organized on the present topic of inherent unsteadiness. In looking for where there would be the most immediate pay-off, they had concluded that effort directed at transition and on demonstrating experimentally what magnitude of effect on on- and off-design behavior were associated with changes in blade spacing, would be the most useful.

Wisler, of General Electric, after describing the difficulty industry would have in contributing financially to the proposed program, gave a listing of issues similar to those mentioned by previous speakers with a rating of 1 to 10 for both level of perceived university/academic interest, and industry's interest. Only with respect to active stall control did his weighting depart from what had been voiced by others, and this was admitted to represent the view of the commercial rather than military engine groups.

Fleeter of Purdue University, in reviewing the status of and need for work in forced response analysis, gave the surprising statistic that fully 12.5% of engine cost results from forced response problems. This does not include the loss of sales that occurs while the problem is being fixed.

The relatively recent field of active stall control was addressed by several speakers. Epstein of MIT reviewed the present understanding of compressor stall and surge. Much now is known. Rotating stall precedes surge and low amplitude rotating disturbances precede rotating stall. Damping the precursor prevents instability. The compressor <u>as a whole</u> goes unstable. Distortion is a major driver, and the instability is governed by the slope of the characteristic. However, in order to develop an accurate method to predict stability boundaries during design, a quantitative connection to the geometry has yet to be made and a valid modelling of the distortion effect is also needed. Tan of MIT showed results that suggested counter-rotation of the fan and core compressor would decrease stall sensitivity to inlet distortion. Both Spang of the G.E. Research Laboratory and Gallops of Pratt & Whitney addressed what is needed to develop practical active control systems for rotating stall. Spang pointed to the need for dynamic modelling, for the development of practical actuator ideas and for robust controllers. Gallops reported that their studies had shown that a 5-10% improvement in stall pressure ratio led to 2-5% reduction in GTOW, 2-5% improvement in range, and as much as 3% improvement in cost. He cited the need to fully understand the stall phenomenon, to understand system response to actuators and to investigate control of combustors as the major research needs.

To summarize, the workshop identified the need for a program of research in three different categories or types of unsteady flow phenomenon in compressors, namely, blade related unsteady flow (basically 2-D unsteady), blade-case related unsteady flow (3-D unsteady) and systems-related unsteady flow. such a program should seek to provide answers to the following questions:

1. BLADE/WAKE EFFECTS

   a) <u>Forced Response.</u> How do you characterize the excitation in the multistage environment, unsteady loads in separated flows and model

shock-secondary layer interaction? How do you analyze linear, then non-linear, interaction of these forcing functions and blade-response-generated unsteady aerodynamics.

b) Optimum Design. How do you choose blade number and spacing to produce the best design point performance within the framework of the present design system? How should you reshape the blading to account for unsteadiness and thereby improve performance.

c) Optimum Stability. How do you select blade number, spacing and shape to maximize compressor stability.

d) Noise. How do you shape, size and space blading to minimize noise.

2. 3-D UNSTEADY EFFECTS

a) Tip-Clearance and Case Wall Flows. How do you shape the blade tip and wall geometry to optimize both design point performance and stall margin.

b) Centrifugal Rotor-Diffuser Flow. How do you shape, position and size diffuser vanes in centrifugal compressors to optimize performance and stability.

3. COMPRESSOR SYSTEM

a) Dynamic Modelling. How do you describe the system behavior in the neighborhood of stall inception.

b) Active & Passive Stabilization. What practical strategies are there for stabilizing, the system, and how do you predict their response.

c) Response to Distortion. How do you introduce inlet distortion to predict dynamic response.

GROUP B

COMMENTS

I think it will be useful to categorize the research programs such that:

1) Fundamental Research: Understanding the flow physics through measurements and computer experiments in simplified geometries so that the effects on heat transfer can be isolated.

   Definitions of unsteady (deterministic) and turbulent (random) compressors of "unsteady flow"

   Characterization of Free Stream Turbulence: what properties are needed to characterize
   (a) Length scales?
   (b) Velocity scales?
   (c) More?

   Characterization of flow out of a combustor
   Mean + Unsteady + Turbulent
   again determination of the necessary parameter

2) Directly applied research
   Limited but realistic measurement of quantities in hot cascades or rotors

3) Research to correct groups 1 and 2 for example, "how the characteristics of free stream turbulence can be related to the geometry of the combustor and the flow through it."

We have been doing modeling studies many decades to obtain heat transfer coefficients. Maybe, we should be thinking more about physics (at least a few groups) of heat transfer and what parameters of the flow if it is related.

In regards to Bob Dring's presentation it was mentioned that in their experiments there was no difference in the heat transfer predictions no Free Stream Turbulence (FST) and 10% (FST). My experience is this area is also the same. In a canonical BL flow the production near the wall brings the level of turbulence up to 10%-12% in the buffer layer and this shear generated turbulence controls the

heat transfer behavior, free stream does not have much effect. However, in cases of higher than 10% FST, FST overcomes the shear generated turbulence near the wall leading to higher than 10% turbulence in the buffer layer and enhancing the heat transfer.

GROUP C
EXPERIMENTS/MEASUREMENTS

What Is The Right Question

Ability to Make Measurements:	7/10
Ability to Determine Right Question or Research Objective:	2/10

1) Is The Question Worth Answering?

2) Is The Answer Already Out There Somewhere?

3) Is This The Right Approach (The Best Way) To Answer The Question?

Modelling is now a product of experimental/numerical analysis synergism, but can also help to "focus" experiments on a particular problem.

1) How do I prevent structural problems?

2) Why/how/by what means/ is film-cooling affected by unsteadiness?

3) What active/passive control breakthroughs can help stall/surge? How can I use understanding to my advantage

4) Is there a difference between stochastic & deterministic unsteadiness? Does it matter?

5) Relevant time scales for heat transfer?

6) Are unsteady effects superimpossible?

7) What are mechanisms for low re flows

8) How does unsteadiness affect turbulence transport coeff?

9) How do time & spatial scales affect measurement?

"TRIADS" and What's Wrong With Them

University -- Government

Industry

Experiment -- CFD Numerical Analysis

Modelling,
Verification

Where Do Industrial Research Labs (UTRC, GE R&D, Etc.) Fit Into This Triad

Need **Strong** Coordination Between These Triads.

- currently **lacking** on a **community-wide** basis in U.S.
- **not** the case in EEC & Japan

How Do We Change This?

Government Supports Students To Do Research In Industry

Government Programs Like NASA Summer Faculty, AFRAP For Faculty -- Industry Not Clear.

Government-University-Industry Consortium

GROUP D
NUMERICAL EXPERIMENTS
SUGGESTIONS

1. Investigate Interrogate Unsteady Flows In 2D Cascades. (Cascade Versus Rotor)

   *Variables: *Blade/Vane Count
   *Gust Amplitude
   *Blade/Vane Spacing

   *Investigate:

   *Loss Mechanism: Effect Of Unsteadiness on Profile Loss
   *Shock Structure/Losses
   *Losses Due To Upstream/Passage Mixing
   *Optimization
   *Aeromechanics/Flutter Boundaries
   *Noise Generation & Propagation
   *Effect On Heat Transfer (Cenvgitivegr Film Cooling)
   *Comparison With Analytical Methods
   *Isolate Various Mechanisms (Inviscid < Viscous) Affecting Performance
   *Rotor/Stator X^n - Off Design

2. One D, Unsteady Pipe Flow. Effect Of Pressure Waves on Overall - h -

3. <u>3D Effects</u>
   (Cascade/Rotor

   *Numerical Experiments To Study Loss Generation Mechanism In Steady - Unsteady Flows - Ndwall Loss - Reduction Or Secondary Flow Loss.

   *Clearance Flow/Losses In Rotors; Investigate Unsteadiness As A Mechanism To Desensitize Tip Clearance Effects

   - Modification Of Flow/Geometry To Reduce Leakage Losses

   *Rotor/Stator (Vane) Interaction

   *Effects On Rotor Performance In Centrifugal 1A X 1A

4. Counter Rotating Rotors
   (Turbines/Compressors).

   - Investigate Possible (?) Gain In Performance

5. Rotating Stall - Investigate/Interrogate Mechanisms/Effects/Minimization

6. Review Panel/Steering Comm

   *Choice Of Geometry/Flow Conditions

   *Right Simulation

GROUP E

DESIGN & CONTROL STRATEGIES

*Active Aeromechanical Control — far term

*Actuation - Surge/Stall Control — near term

- High Bandwidth/High Stroke
- Identify Fluid Disturbance Desired

*3-D Compressible, Non-Linear Stability Models — near term

*Controls Modelling Technology For Fluid Systems

Active Combustion Control For Low NO_X

Control Algorithms

Adaptive/Active Casings

• LIST OF ATTENDEES

LIST OF ATTENDEES

Abhari, Reza
Textron Lycoming, 550 Main Street, Dept. LSD11, Sratford, Ct 06497

Adamczyk, J
NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, OH 44135

Alverson, Richard
Allison Gas Turbine Division GMC, PO Box 420, MST14, Indianapolis, IN 46206-0420

Ames, Forrest
Allison Gas Turbine Division GMC, PO Box 420 Speed Code W-16, Indianapolis, IN 46206-0420

Atassi, H.
University of Notre Dame, 365 Fitzpatrick Hall, Notre Dame, IN 46556

Baghdadi, Sam
Pratt & Whitney, PO Box 109600, W. Palm Beach, FL 33410-9600

Bajaj, A.K.
Purdue University, West Lafayette, IN 47907

Bober, Lawrence
NASA Lewis Research Center, 21000 Brookpark Rd. M/S 77-6, Cleveland, OH 44135-3191

Bushnell, Dennis
NASA-Langley Research Center, M/S 197, Hampton, VA 23681

Camci, Cengiz
Pennsylvania State Univ., 153-E Hammond Building, University Park, PA 16802-1400

Capece, Vincent
Univ. of California Davis, Dept. Mech & Aero Engr., Davis, CA 95616-5294

Chriss, Randy
NASA Lewis Research Center, 21000 Brookpark Rd, MS5-11, Cleveland, OH 44135

Chyu, Mingking
Carnegie Mellon University, Mechanical Engr Dept/MCU, Pittsburgh, PA 15213

Coons, Leland
Pratt & Whitney, 400 Main St., E. Hartford, CT 06108

Copenhaver, William
WL/POTX, 2450 Spicer Rd., Beavercreek, OH 45431

Cross, Charles
US Air Force, WL/POTC Bldg. 18, 1950 Fifth St., Wright-Patterson AFB, OH 45433-7251

Davis, Roger
United Technologies Res.Ctr., MS 129-20 411 Silver Lane, East Hartford, CT 06108-1049

Delaney, Robert
Allison Gas Turbine Div., PO Box 420, Indianapolis, IN 46206

Doligalski, Thomas
U.S. Army Research Office, P.O. Box 12211, Res. Triangle Pk., NC 27709

Dorney, Daniel J.
Western Michigan University, 2079 Kohrman Hall, Kalamazoo, MI 49008-5065

Dring, Robert P.
United Tech. Res. Center, Silver Lane, East Hardford, CT 06108

Dunn, Michael
Calspan Corporation, 4455 Genesee Street, Buffalo, NY 14225-1967

Eckert, Ernst
Univeristy of Minnesota, 60 W. Wentworth Ave., West St. Paul, MN 55118

Epstein, Alan
MIT, RM 31-266, Cambridge, MA 02139

Fabian, Mike
USAF Academy/Univ Notre Dame, PO Box 6713, South Bend, IN 46660

Fagan, J.R. Jr.
Allison Gas Turbine, 20001 S. Tibbs Ave., Indianapolis, IN 46206-4812

Fang, Jisheng
University of Notre Dame, 365 Fitzpatrick Hall, Notre Dame, IN 46556

Fant, Daniel
AFOSR, 110 Duncan Ave., Ste. B115, Bolling AFB, DC 20332-0001

Fleeter, Sanford
Purdue University, Mechanical Engineering, West Lafayette, IN 47907

Gallops, G. William
Pratt & Whitney, PO Box 109600, West Palm Beach, FL 33410-9600

Gemmen, Randall
U.S. Department of Energy, PO Box 880, Morgantown, WV 26507-0880

Goldstein, Richard
University of Minnesota, 111 Church Ste. SE, Minneapolis, MN 55455

Hah, C.
NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, OH 44135

Halstead, David
Iowa State University, 9450 Woodland Hills Dri., Hamilton, OH 45011

Heidmann, James
NASA Lewis Research Center, 21000 Brookpark Rd., Cleveland, OH 44135

Hilbert, Gary
Pratt & Whitney, 400 Main St., M/S 163-09, E. Hartford, CT 06108

Hoyniak, Daniel
NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, OH 44135

Incropera, F.
Purdue University, West Lafayette, IN 47907

Johnson, Robert
Purdue University, Mechanical Engineering, West Lafayette, IN 47907

Jumper, Eric
University of Notre Dame, Hessert Ctr. for Aerospace, Notre Dame, IN 46556-5684

Kerrebrock, Jack
MIT, 33-411 MIT, Cambridge, MA 02139

Khalid, Syed
Pratt & Whitney, PO Box 109600, West Palm Beach, FL 33410

Kielb, Robert
GE Aircraft Engines, One Newman Way, MD X412, Cincinnati, OH 45215-6301

Kim, Chan
NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, OH 44135

Kokini, Klod
Purdue University, 4814 Doe Path Ln., Lafayette, IN 47905

Kurkov, Anatole
NASA Lewis Research Center, 21000 Brookpark Rd., Cleveland, OH 44135

Kurosaka, Mitsuru
University of Washington, 7529 - 172nd St. SW, Edmonds, WA 98026

Lakshminaragana, Budugur
Penn State University, 153 Hammond Bldg., University Park, PA 16802

Lavrich, Philip
United Technologies Research, 411 Silver Lane, East Hartford, CT 06108

Lawless, Patrick
Purdue University, Chaffee Hall, West Lafayette, IN 47907

Lewalle, Jacques
Syracuse University, 151 E.A. Link Hall, Syracuse, NY 13244-1240

Liu, Feng
Univ. of California, Irvine, Dept. of Mech & Aerospace Engr, Irvine, CA 92715

Lucci, Barbara
NASA Lewis Research Center, 1835 Ridgeview Dr, Wickliffe, OH 44092

MacArthur, Charles
AF Wright laboratory, 1950 fifth St., WPAFB, OH 45433-7251

Maciejewski, Paul
University of Pittsburgh, Mech.Engr. Dept. (648 BEH), Pittsburgh, PA 15261

Madavan, Nateri
MCAT Inst/NASA Ames Res. Ctr., 3933 Blue Gum Drive, San Jose, CA 95127

McDonald, Henry
Pennsylvania State University, Applied Research Laboratory, State College, PA 16804

Moffat, Robert
Stanfvord University, Dept. of Mechanical Engr., Stanford, CA 94305

Moore, Franklin
Cornell University, Upson Hall, Ithaca, NY 14853-7501

Murthy, SNB
Purdue University, Mechanical Engineering, West lafayette, IN 47907

Nett, C.
Georgia Inst. of Technology, 00999

Newman, Fred
NASA Lewis Research Center, 21000 Brookpark Rd., Cleveland, OH 44135

Ng, Wing
Virginia Tech., 114 Randolph Hall (Mech Engr.), Blacksburg, VA 24061-0238

Nwokah, O.D.I.
Purdue University, Mechanical Engineering, West lafayette, IN 47907

Okiishi, Ted
Iowa State University, 2025 Black Engr. Bldg., Ames, IA 50011

Plesniak, Michael W.
Purdue University, Thermal Sci. 1003 Chaffee Hall, West Lafayette, IN 47907

Rai, M.
Nasa Langley Research Center, Hampton, VA 23681

Richardson, Scott
U.S. Air Force, WL//POTX Bldg. 18, 1950 5th St., WPAFB, OH 45433-7251

Rivir, R.
Wright Laboratory, Wright Patterson Air Force Base, OH 45433

Shreeve, Raymond
Naval Postgraduate School, Code AA/SF, Monterey, CA 93943-5000

Simoneau, Robert J.
NASA Lewis Res. Ctr., MS 5-11, 21000 Brookpark Rd., Cleveland, OH 44135-3191

Simpson, Roger
VA Polytechnic Inst., 605 Preston Ave., Blacksburg, VA 24060

Sinha, Sumon
University of Mississippi, Mechanical Engineering Department, University, MS 38677

Spang, H. Austin
GE Research & Development, Box 8 KW0220, Schenectady, NY 12301

Stefko, George
NASA Lewis Research Center, 21000 Brookpark Rd, Cleveland, OH 44135

Strazisar, Tony
NASA Lewis Research Center, 21000 Brookpark Rd M/S 5-11, Cleveland, OH 44135

Suder, Kenneth
NASA Lewis Research Center, 21000 Brookpark Rd., Cleveland, OH 44135

Tan, Choon
MIT, 77 Massachusetts Ave., Cambridge, MA 02139

Vanosdol, John
U.S. Department of Energy, 3610 Collins Ferry Road, Morgantown , WV 26505

Verdon, Joseph
United Technologies Res.Ctr., 411 Silver Lane, MS 129-20, East Hartford, CT 06108

Wang, Ting
Clemson University, Department of Tech. Engr., Clemson, SC 29634-0921

Waterman, William
Allied Signal Engines, PO Box 52181, MS 503-4AB, Phoenix, AZ, 85072-2181

Wellborn, Steven
NASA Lewis Research Center, 21000 Brookpark Rd., MS 5-11, Cleveland, OH 44135-3191

Wisler, David
GE Aircraft Engines, One Newman Way, Cincinnati, OH 45215

Yang, H.T.
Purdue University, West Lafayette, IN 47907

Yavuzkurt, Savas
Penn State University, 338C Reber Building, University Park, PA 16802